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EVALUATION OF TORSIONAL PROPERTIES OF SPRING MATERIALS

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13. ABSTRACT
Torsional properties of various spring materials were evaluated. All materials tested were of solid circular cross section with a diameter of approximately.200 inch. Test specimens were twisted on a torsion tester equipped with an automatic recorder by which torque-angular strain diagrams were plotted. Diagrams were analyzed and measurements made to determine values for proportional and elastic limits. The amount of increase to the proportional and elastic limits that results from strain hardening was determined. The effects of shot peening on the elastic limit were also studied. Strain hardening of the high carbon steels had little effect on the proportional limit, but did produce a substantial increase in the elastic limit. The shot peening operation had little noticeable effect on the torsional properties. Detailed tables of torsional properties are presented and results discussed.

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5. Strain Hardening						
6. Shot Peening						

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ABSTRACT

Torsional properties of various spring materials were evaluated. All materials tested were of solid circular cross section with a diameter of approximately .200 inch. Test specimens were twisted on a torsion tester equipped with an automatic recorder by which torque-angular strain diagrams were plotted. Diagrams were analyzed and measurements made to determine values for proportional and elastic limits. The amount of increase to the proportional and elastic limits that results from strain hardening was determined. The effects of shot peening on the elastic limit were also studied. Strain hardening of the high carbon steels had little effect on the proportional limit, but did produce a substantial increase in the elastic limit. The shot peening operation had little noticeable effect on the torsional properties. Detailed tables of torsional properties are presented and results discussed.

CONTENTS

OBJECTIVE

The objectives of this project were (1) to evaluate the torsional properties of various spring materials, (2) to determine the amount of increase to the proportional and elastic limits from strain hardening of the material and (3) to determine the effect on the torsional properties produced by shot peening of the material.

INTRODUCTION

The suitability of a material for helical compression and extension spring applications can best be decided by consideration of its torsional properties. The torsional elastic limit and yield point, rather than the tensile strength, provide more reliable criteria to determine the energy storing capacity of a spring, its resistance to permanent set, and the capacity for a satisfactory spring service life. This is true because the principal stress in a helical spring under compression is torsional, and the material behaves essentially as a straight bar twisted under torsion. The torsion moment, T, which produces the twist is the product of two factors, the load, P, acting along the axis of the helical spring and the effective moment arm, D/2, where D is the mean coil diameter. The formula for the torsional stress is obtained simply by the dividing of the torsion moment acting on the spring by the section modulus in torsion, which for round wire is $\pi d^3/16$; where d is the diameter of the wire.

$$\text{Torsional Stress, } S = \frac{\frac{PD}{2}}{\frac{\pi d^3}{16}} = \frac{8PD}{\pi d^3} \qquad (1)$$

This formula is related to the one used for calculating the stress in torsion bar springs.

$$\text{Torsional Stress, } S = \frac{16T}{\pi d^3} \qquad (2)$$

DISCUSSION

Material

Torsional properties of the following spring materials were measured in this study. All the material had solid circular cross sections.

Material	Diameter (inch)
Music Wire, QQ-W-470	.200
Hard Drawn, QQ-W-428, Type II	.207
Chrome Vanadium, QQ-W-412, Comp. I	.207
Oil Tempered, QQ-W-428, Type I	.200
Stainless Steel, QQ-W-423, Comp. FS302	.207
Stainless Steel, QQ-W-423, Comp. FS316	.187

Material was obtained from the supplier so that the diameters were as close to .200 inch as possible. Material was cut to 12 inches in length, this allowed 5.5 inches of gauge length specimen after the rod was secured into the locking chucks of the torsion tester. The application of right angle bends at the ends of the rod for anchoring purposes was unnecessary. The material was inserted in straight form directly into the gripping jaws of the chucks.

Testing Equipment and Procedures

The torsion tester used to measure the torsional properties is shown in Photograph 11-199-2086/AMC-72 in the Appendix. The tester consists of two major units, an indicating unit and a loading unit. The loading unit in turn is composed of two separate parts, a weighing head and a power or load applying head. A torque arm which is permanently fixed within the weighing head transmits the torsional load to a load cell which directly converts the torque value to an electrical signal that is then displayed on the indicating unit. The power head is mounted on rollers and is free to travel on round rails to permit rapid lateral adjustment for varying specimen lengths, and automatic compensation for changes in specimens length during test. All loading was performed with the power head rotating in a counter-clockwise direction.

The tester is equipped with a recorder by which the load-angular strain relationship of the specimen under test is automatically plotted. The torque load is plotted along the ordinate in terms of inch - pounds and the angular strain is shown along the abscissa in degrees. All testing was performed with a torque scale range of 0-500 inch - pounds, that is, each major division along the ordinate represents 100 inch - pounds. The strain magnification was selected so that each inch along the abscissa represents 10 degrees. The test speed both for loading and unloading was at 60 degrees per minute. The proportional limit and the elastic limit in torsion for each material were read directly from the load - strain curve. The proportional limit is that point on the load - strain diagram where the curve begins to depart from a straight line. Beyond the

proportional limit, unit deformation begins to increase at a faster rate than does the unit stress. The elastic limit is that point on the load-strain curve where further deformation results in permanent set to the material.

Test Results

Material As Received, Not Shot Peened

The load-strain diagram of the initial loading that was applied to the music wire material is shown in Figure 1 in the Appendix. The measured proportional limit and elastic limit are respectively 150 inch-pounds and 205 inch-pounds. Note that a sizable difference exists between these two values; this is in contrast to the material loaded under tension where, generally, the proportional limit and the elastic limit practically coincide. The loading extends beyond the elastic limit and into the plastic range, as can be seen in Figure 1. The angular deflection of 25.5 degrees that occurred beyond the elastic limit resulted in a permanent set to the material. The slope of the unloading line is approximately equal to that of the elastic loading curve. The results of subsequent loadings that were made to the same piece of music wire are shown in Figures 2, 3, and 4. In each case loading was applied beyond the elastic limit and into the plastic region of the material. The proportional limit increased to 160 inch-pounds and the elastic limit increased to 235 inch-pounds due to the effect of the strain hardening of the material (Figure 2). Further cold working had no effect on the proportional limit; however, it did increase the elastic limit slightly to 250 inch-pounds (Figures 3 and 4). Torsion testing of spring materials in this study has shown that little, if any, changes occurred in the physical properties after the fourth loading. The load-strain diagram of the music wire material torqued up to its elastic limit of 250 inch-pounds and then unloaded as shown in Figure 5. Note that the unloading line returned to the original position; no set occurred in the material since the elastic limit was not exceeded. Some energy dissipation occured in the loading and unloading cycle as represented by the area between the two curves. This energy has been lost mainly in the form of internal friction within the rod.

Torsional properties of subsequent materials will be shown only at the following three important stages of loading: initial loading, fourth loading, and a complete cycle within the elastic range. The torsional properties of hard-drawn material QQ-W-428, Type II are represented in Figures 6, 7, and 8. Strain hardening had a slight effect on the proportional limit, i. e., its value was increased from 150 to 160 inch-pounds. However, strain hardening did have a profound effect on the elastic limit i. e., its value was increased 25 per cent, from 200 to 250 inch-pounds.

The hard-drawn material can safely withstand a stress of 144,000 psi (250 in.-lb.) without incurring any permanent set (Figure 8).

Torsional properties of chrome-vanadium material and its reaction to strain hardening are illustrated in Figures 9, 10, and 11. The proportional limit increased from 190 to 240 inch-pounds, and the elastic limit similarly increased from 225 to 275 inch-pounds.

A slight change occurred in the torsional properties of oil-tempered material. Strain hardening had no effect on the proportional limit; its value remained at 150 inch-pounds throughout the testing (Figures 12 and 13). The elastic limit increased by 30 inch-pounds, from 190 to 220 inch-pounds.

The test results for stainless steel, FS302 and stainless steel, FS316 are shown in Figures 15 and 16, and in Figures 18 and 19, respectively. The proportional limit for the FS302 type increased from 100 to 140 inch-pounds, and its elastic limit increased from 155 to 200 inch-pounds. The initial proportional and elastic limits for stainless steel, FS316 were 100 inch-pounds and 130 inch-pounds. Each value was increased by 20 inch-pounds because of strain hardening to 120 and 150 inch-pounds.

The torsional properties of all the materials for convenient comparison are listed in Table 1 of the Appendix. Stress values shown on Table 1 were calculated with the use of Equation 2

$$\text{Torsional stress, } S = \frac{16T}{\pi d^3} \qquad (2)$$

The most relevant value to spring design is the final elastic limit since the point at which a spring will commence to set and fail to support the applied load is determined by this value. The music wire and chrome-vanadium materials have the highest elastic limits and are about equal (Table 1). The hard-drawn and oil-tempered materials which have comparable chemical compositions also have similar elastic properties. The stainless steels, FS302 and FS316, have approximately equal elastic strengths, which were the lowest of all measured values. The strain hardening of the high carbon steels had a greater influence on the elastic limit than on the proportional limit. This is particularly true for the oil-tempered material whose proportional limit remained unchanged, but its elastic limit was increased by 30 inch-pounds because of the cold working.

The following standard formula by which the torque-deflection relationship is expressed enables one to describe the test curves very closely up to the proportional limit of the material.

$$T = \frac{Gd^4\theta}{583.6L} = \frac{11.5 \times 10^6 \, (.207)^4\theta}{583.6 \, (5.5)} \qquad (3)$$

T - Applied torque load, inch-pounds

G - Modulus of elasticity in torsion, pounds per square inch

d - Diameter of rod, inches

θ - Angular twist over gauge length, degrees

L - Gauge length, inches

For example, the measured and calculated torque-angular deflection values for the hard-drawn material (Figure 7) which has a proportional limit of 160 inch-pounds is as follows:

Deflection	Measured Torque	Calculated Torque
5 Deg.	35 In.-Lb.	33 In.-Lb.
10	65	66
15	95	99
20	120	132
25	150	164
30	170	197
35	195	230

Shot-Peened Material

Six materials of the same type were also shot peened in accordance with the following procedure:

(1)	Type of shot material,	steel
(2)	Shot size,	.033 in.
(3)	Shot hardness,	R_c 45-50
(4)	Almen intensity,	.012-.016A

This procedure is the standard method practiced by the Arsenal Operations Directorate in the shot peening of production springs with wire diameters of .150-.500 inch.

Load-strain curves for the shot-peened material are given in Figures 21 to 26. For convenient comparison, each figure contains 2 curves, showing the initial loading and the final loading after the material has been fully strain hardened. The initial and final elastic limits for the as-received material and the shot-peened material together with the associated stress values are listed in Table 2 of the Appendix. The peening operation had little noticeable effect on the elastic limits. (Table 2). As a matter of fact, no changes occured in the elastic properties of the hard-drawn and oil-tempered materials.

Bauschinger Effect Produced by Torque Reversal

The interesting effect caused by the reversing of the twisting moment is shown in Figure 27. The initial loading of the material is shown by curve OAB. The rod is then unloaded along curve BDO, then torqued in the opposite direction along curve OE, and then allowed to return to 0 torque, as shown by curve EF. The proportional and elastic limits in the original loading direction are respectively 160 and 210 inch-pounds. However, these values decrease considerably when the bar is twisted in the opposite direction. Also, in the reversed direction, the proportional and elastic limits coincide at the value of 40 inch-pounds. This sharp decrease in physical properties is known as the Bauschinger effect and this effect is used to explain why spring manuals contain caution notes that torsion bars be loaded only in the same direction as that of the presetting torque.

The Bauschinger effect is produced by two factors. One is the nonuniformity of yielding in a polycrystalline metal. Because the crystals are oriented at random throughout the metal, they yield by different amounts so that on a microscopic scale the stress varies slightly from crystal to crystal. When the member is unloaded, it contracts until the average stress is zero. However, the crystals that yielded the least do not quite return to zero, these remain stressed in the original direction while those that yielded the most go beyond zero and are stressed in the opposite direction. Thus, microscopic residual stresses called Heyn stresses or textural stresses exist throughout the metal. Therefore, when the twisting moment is reversed, the crystals that already have residual stresses in that reversed direction will yield at a lesser stress level and the overall yield stress will be lower.

The effect observed in polycrystals cannot be attributed entirely to these residual stress, and the effect in single crystals cannot be explained by them. Another factor is the behavior of dislocations that can be explained as follows. When the material yields in the first direction,

the dislocations move through the crystal structure until obstacles are encountered by which progress is slowed down or stopped entirely. As other dislocations approach, they also are slowed or stopped, and strain hardening takes place. When the load is removed, the elastic strains are recovered, but the dislocations still remain immobile and under some strain from having been crowded together behind the various obstacles. Consequently, they move more easily in the reverse direction and at a lower than normal stress. This phenomenon enables one to explain the Baushinger effect in single crystals and, at least, part of that in polycrystals

CONCLUSIONS

1. Strain hardening had a minor effect on the proportional limits of the high-carbon steels that were tested, but did produce a noticeable effect on their elastic limits.

2. The formula $T = \frac{Gd^4\theta}{583.6L}$ approximates the test results very closely up to the proportional limit of the material.

3. A sizable difference exists between the proportional and elastic limits in torsion; this is in contrast to the material loaded under tension, where generally these limits are approximately equal.

4. Music wire and chrome vanadium had the highest torsional elastic limits of the six materials tested.

5. The shot-peening operation had little noticeable effect on the elastic limits of the materials. Evidently, the beneficial effects of shot peening can not be measured in terms of the elastic limit.

6. A torque-deflection diagram provides an excellent criterion for the determination of quality spring material.

RECOMMENDATIONS

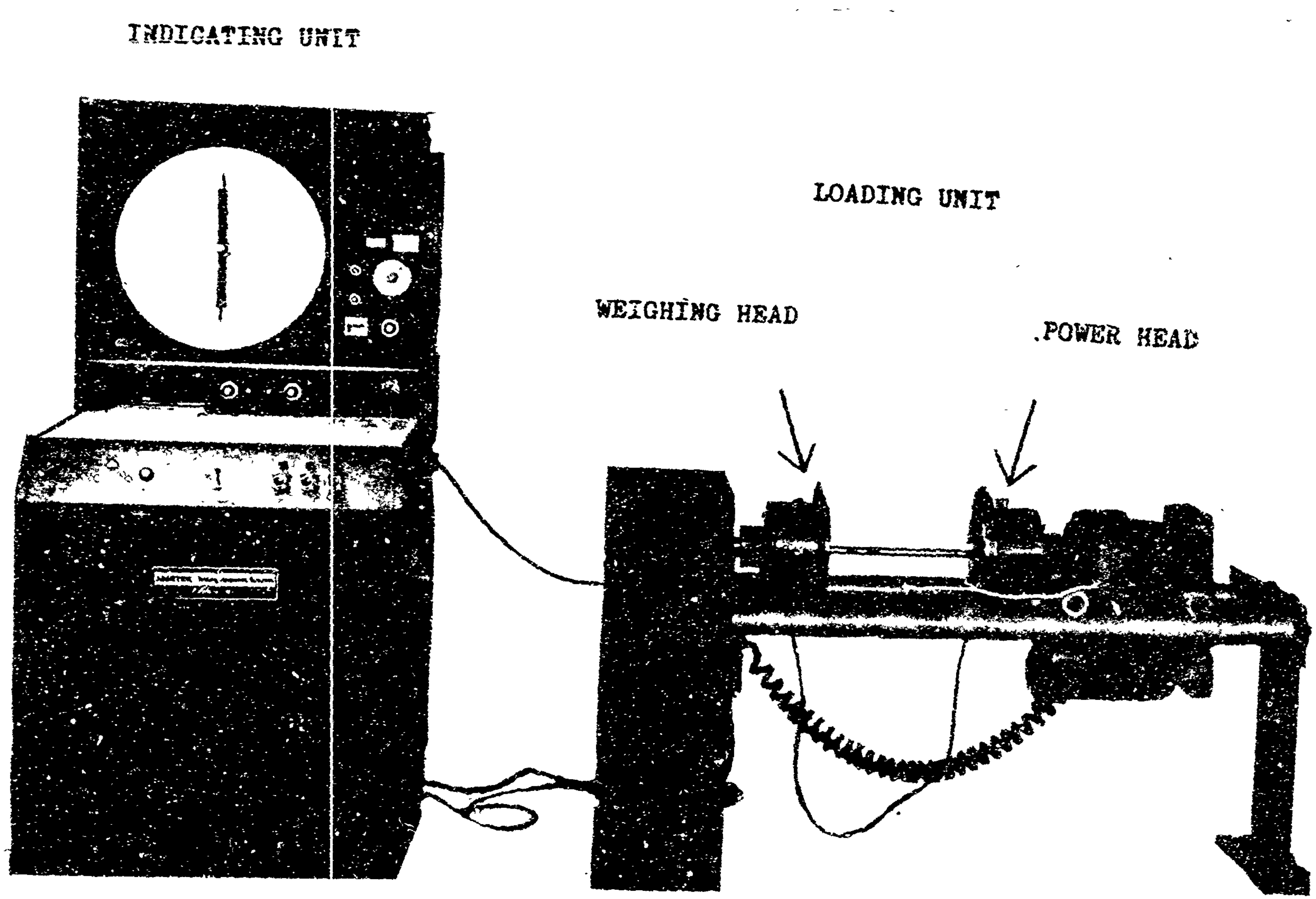
1. Torsional properties should be considered in the evaluation of material for spring applications

2. Critical springs should be strain hardened by presetting to increase the elastic limit of the material.

3. Music wire and chrome-vanadium materials should be recommended generally for highly stressed applications because of their higher torsional elastic limits

4. Stainless steel materials should be recommended for only those areas that involve corrosive or high temperature environments.

APPENDIX



TORSION TESTER

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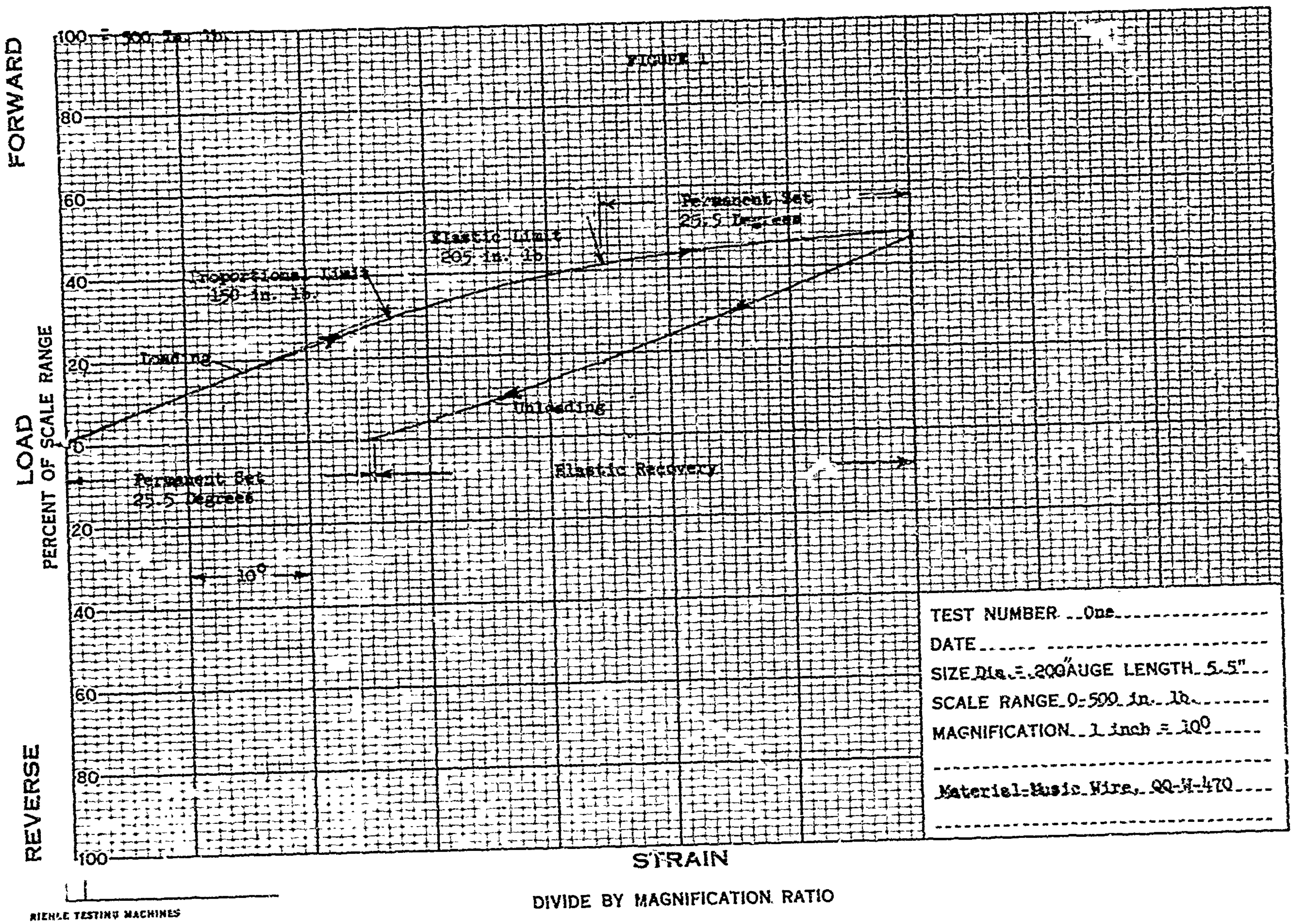

FIGURE 1 Material - Music Wire QQ-W-470

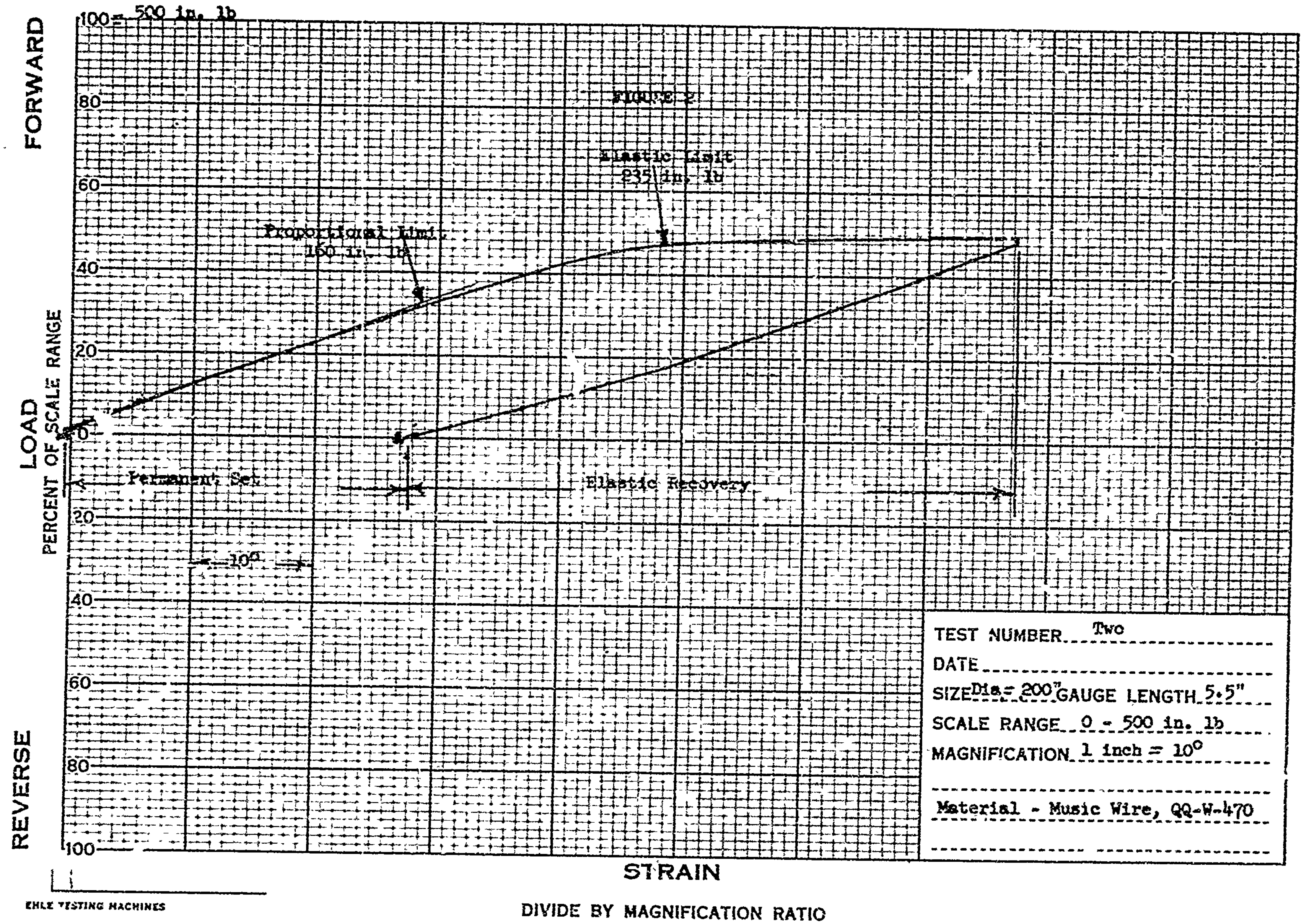

FIGURE 2 Material - Music Wire, QQ-W-470

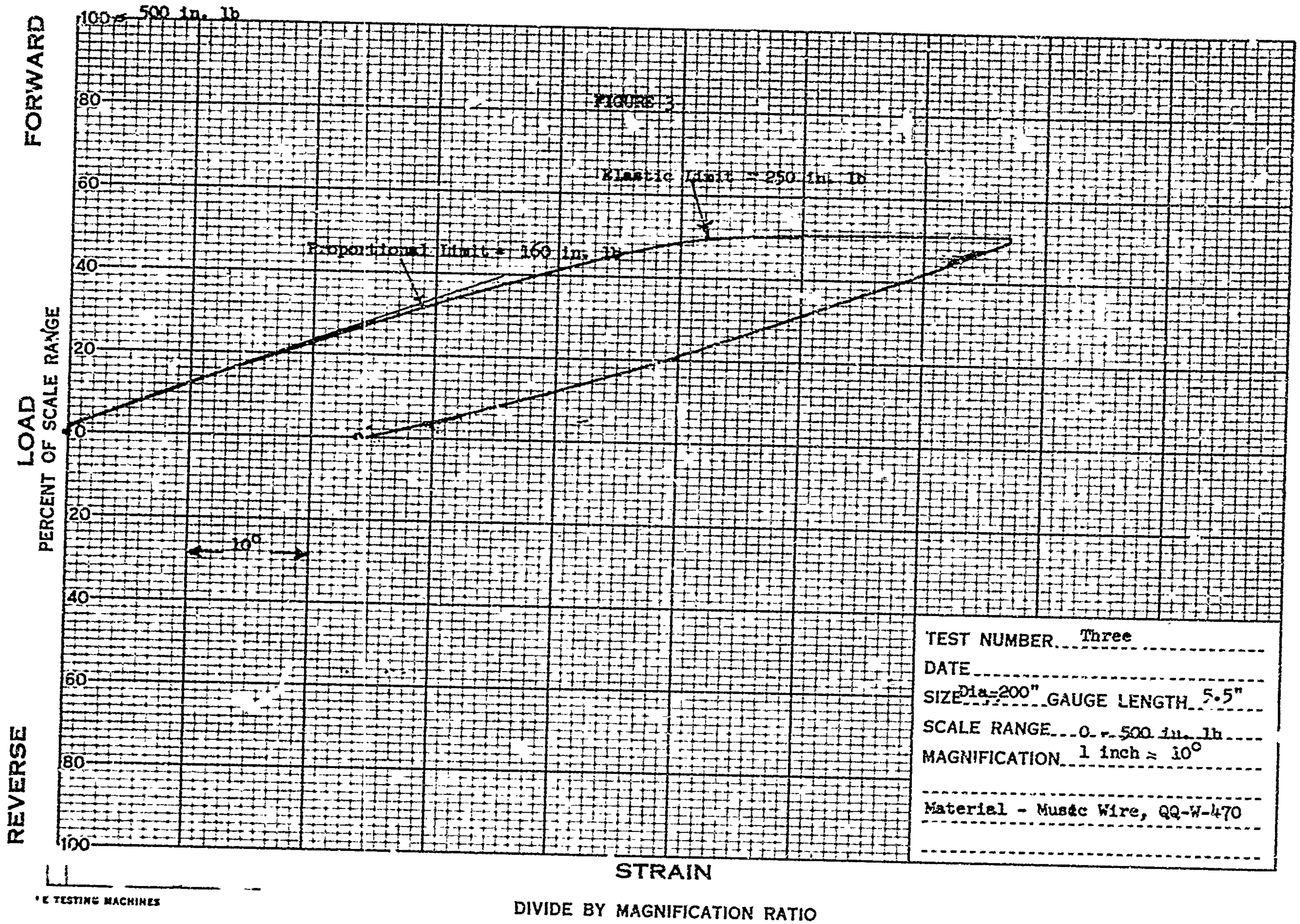

FIGURE 3 Material - Music Wire, QQ-W-470

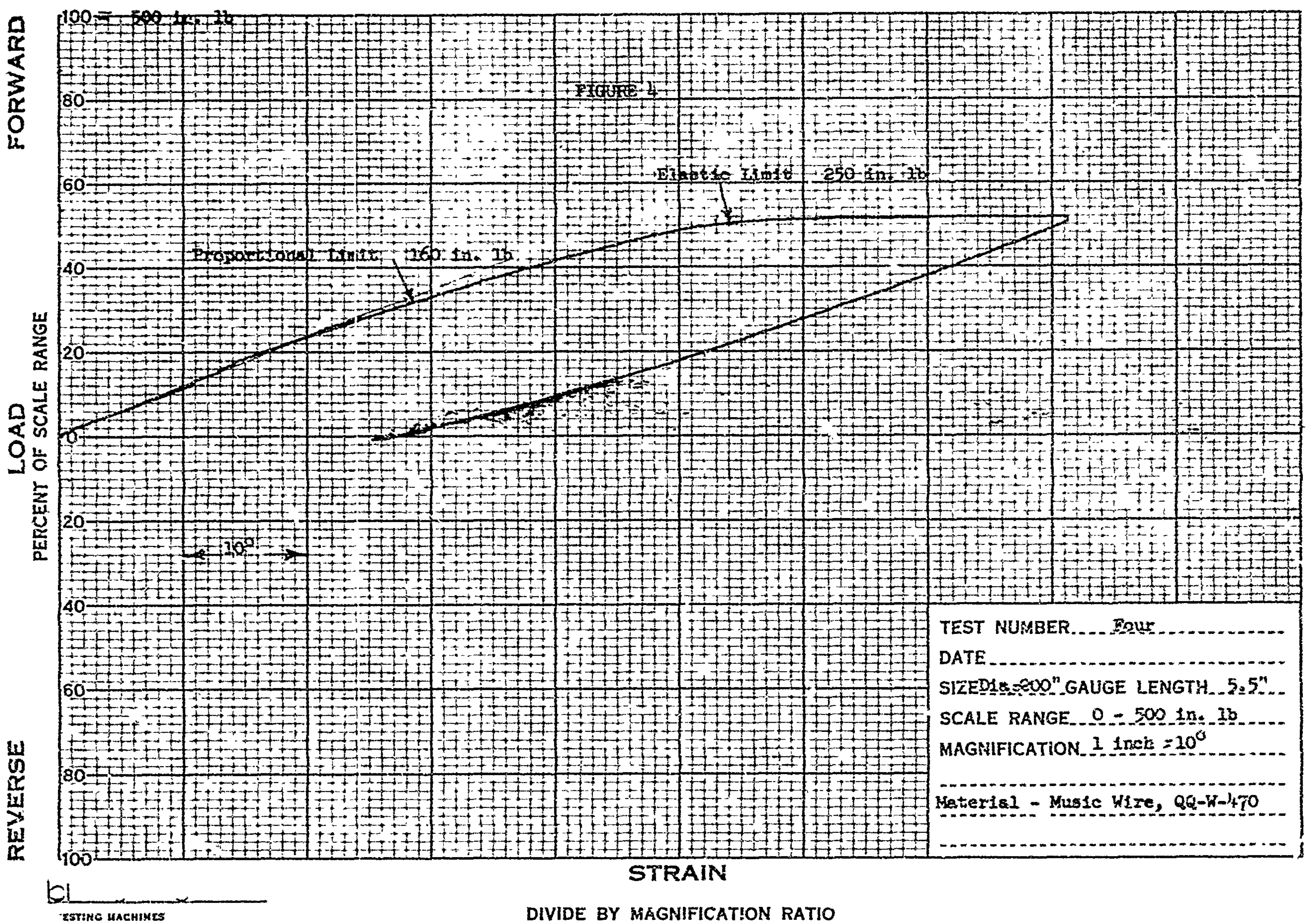

FIGURE 4 Material - Music Wire, QQ-W-470

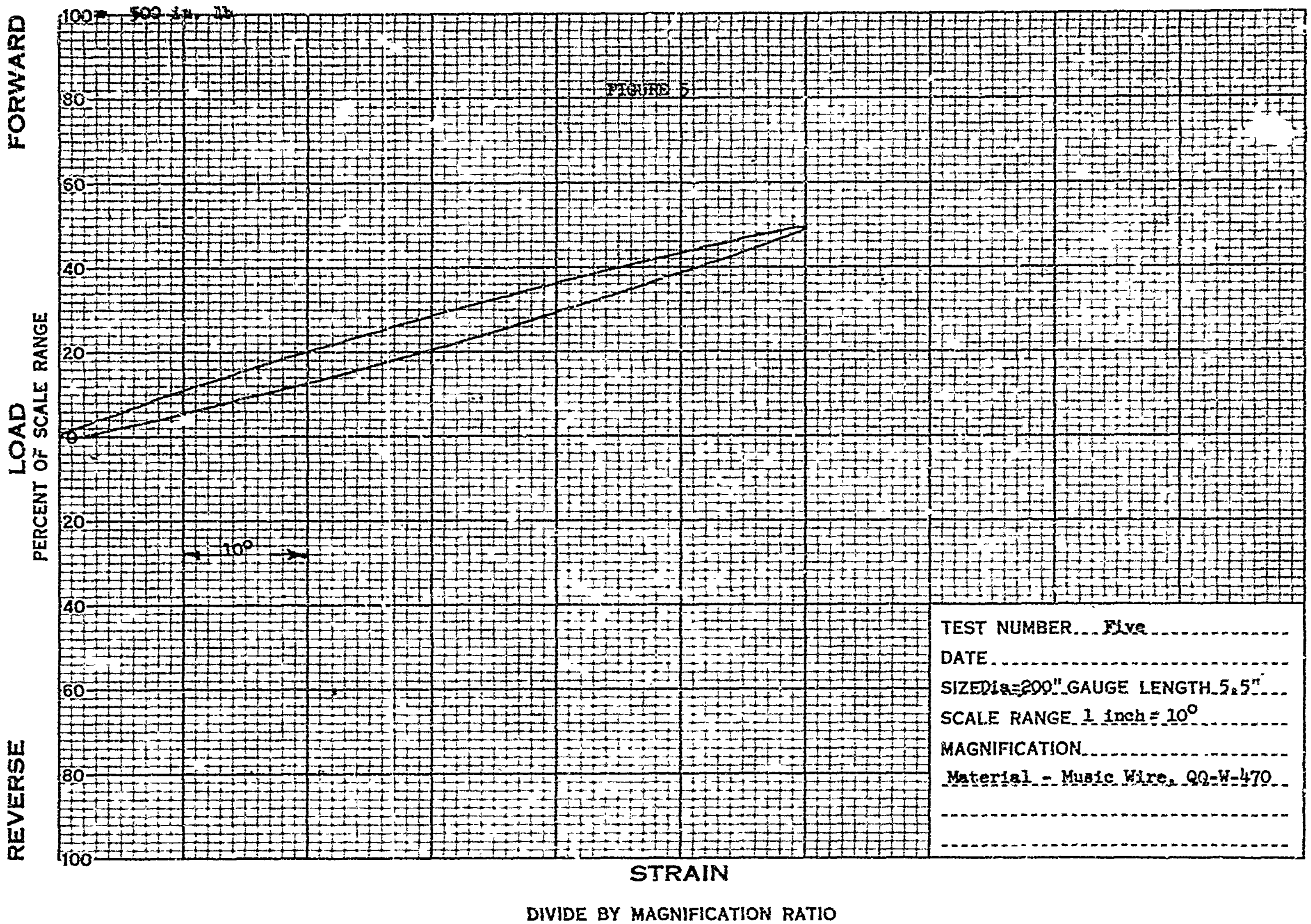

FIGURE 5 Material - Music Wire, QQ-W-470

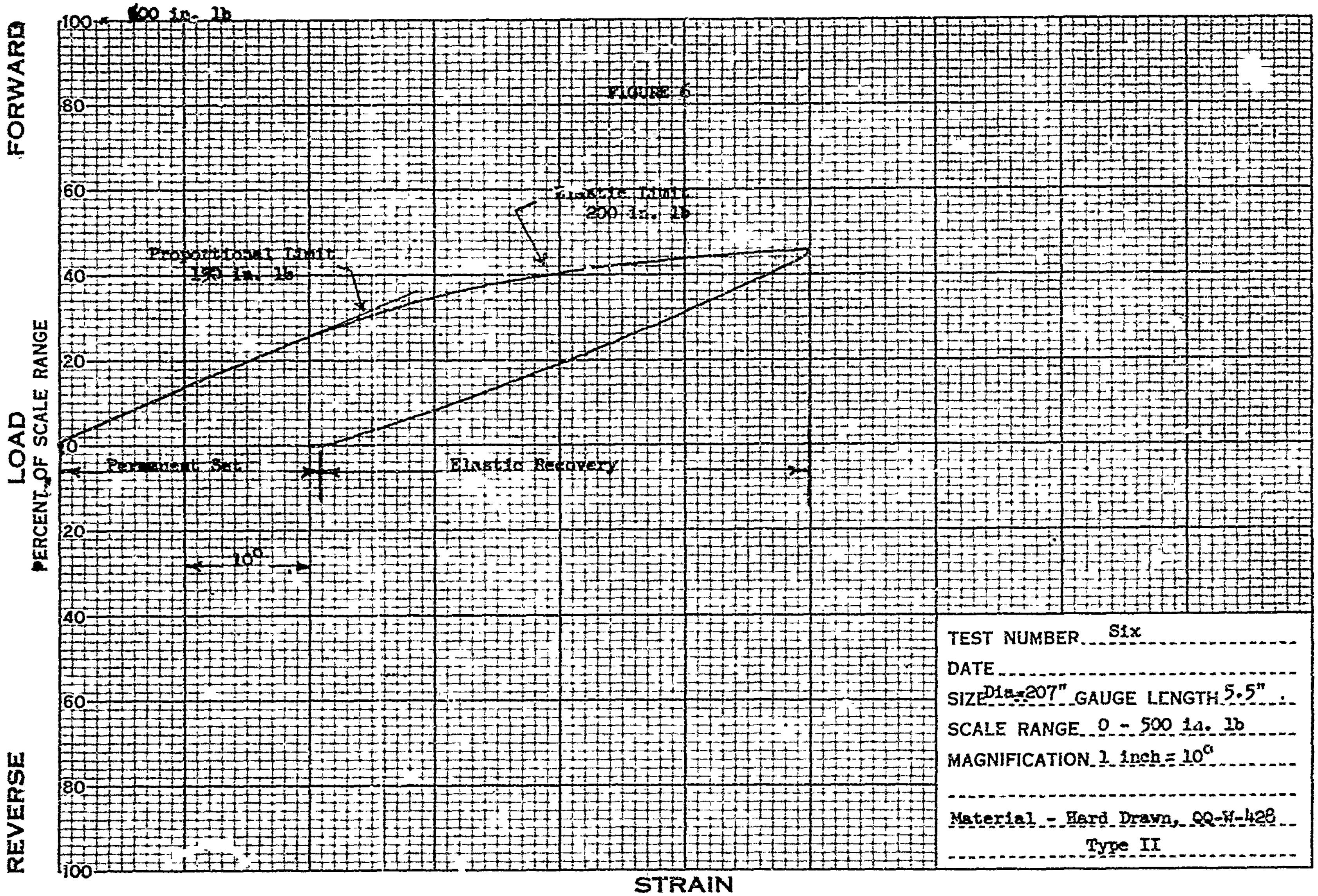

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FIGURE 6 Material - Hard Drawn, QQ-W-428 Type II

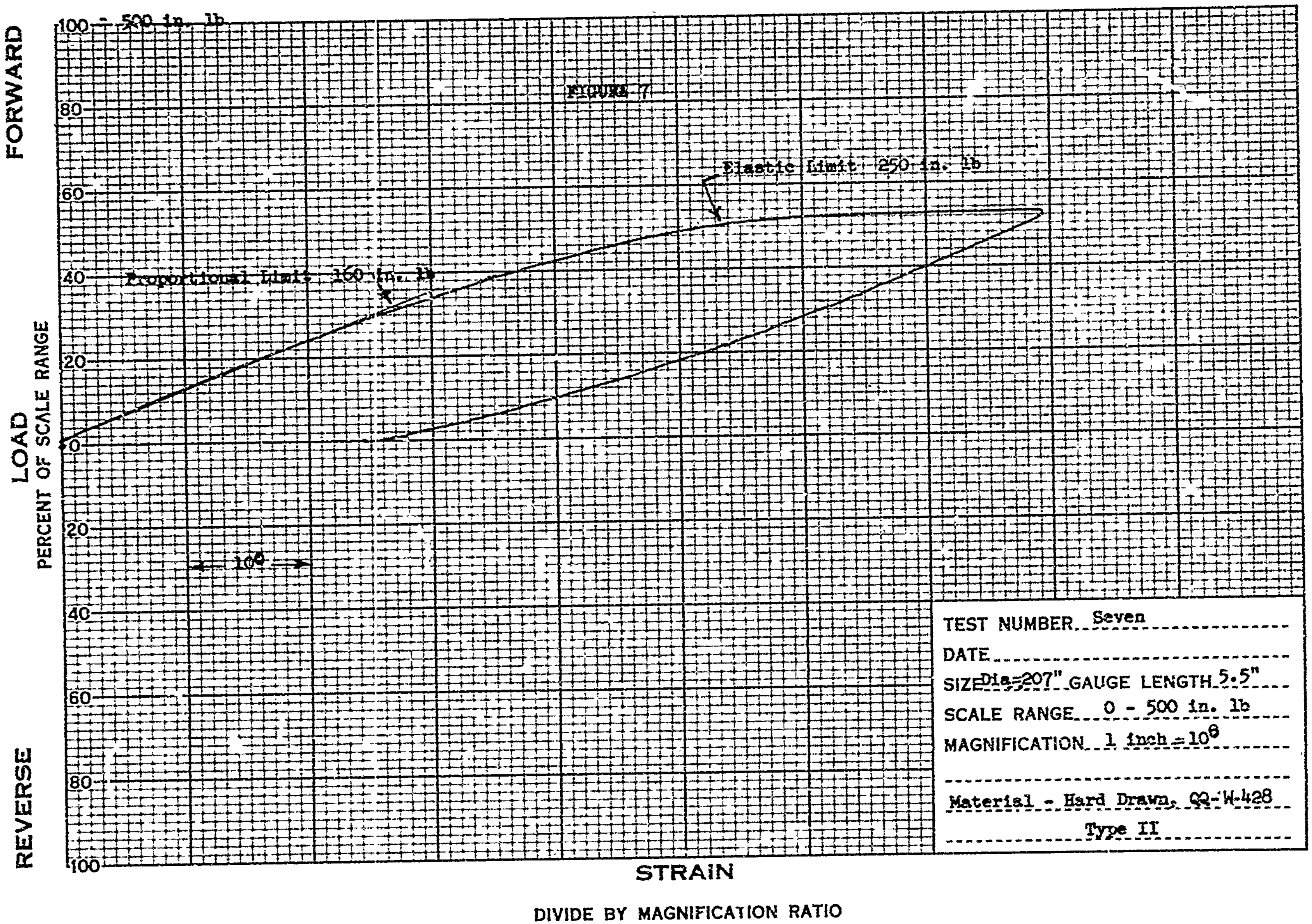

FIGURE 7   Material - Hard Drawn, QQ-W-428
Type II

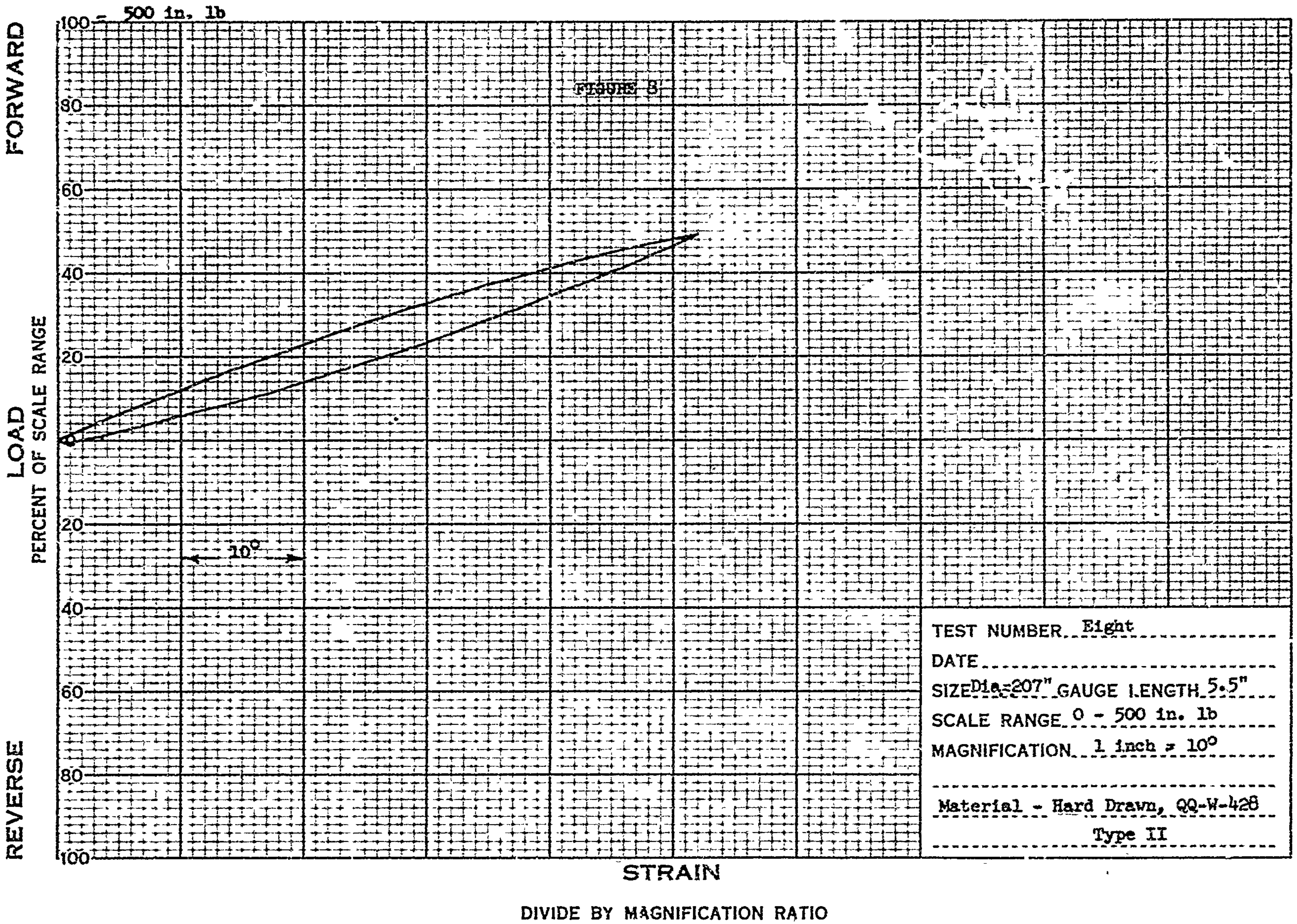

FIGURE 8

Material - Hard Drawn, QQ-W-428
Type II

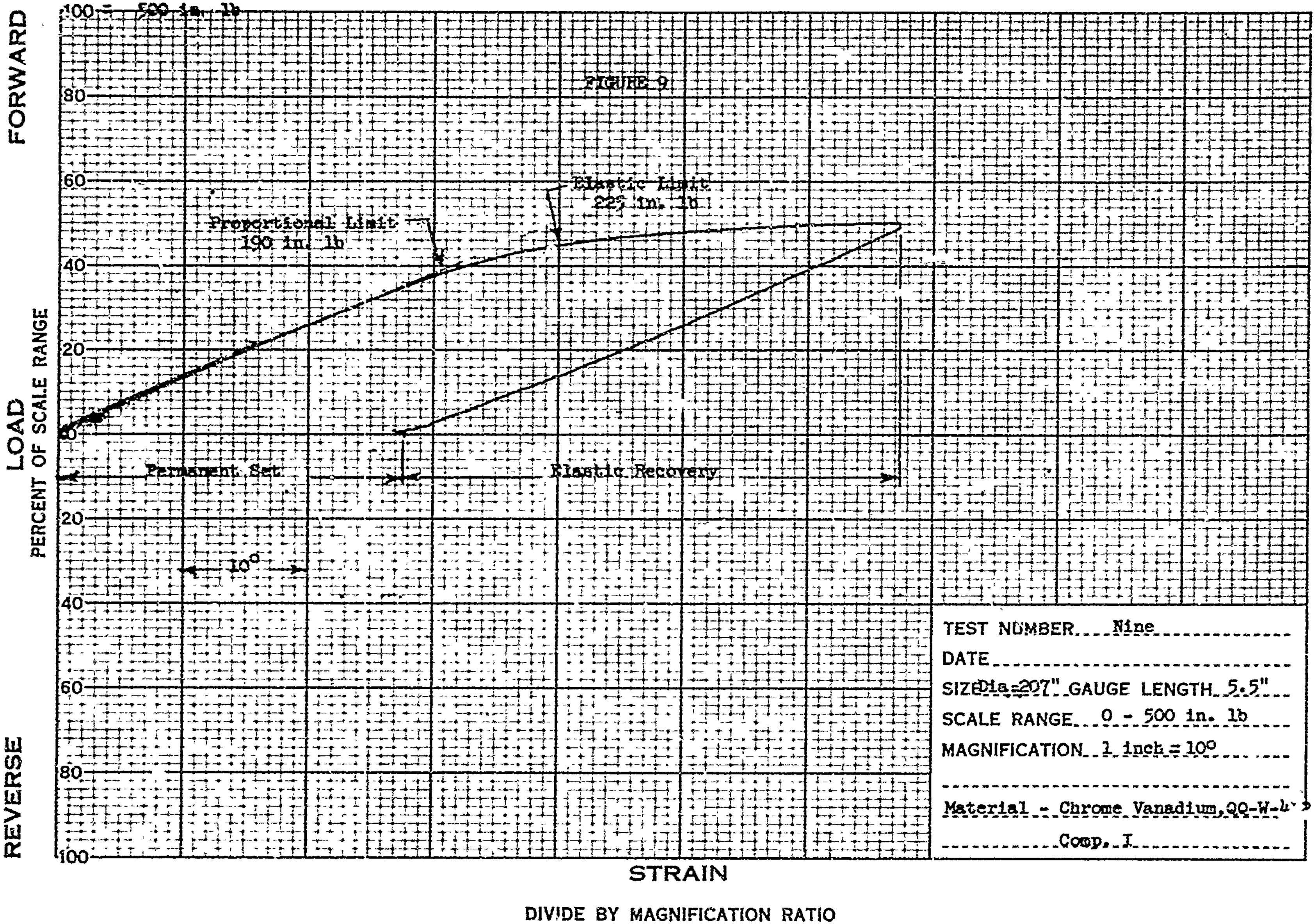

FIGURE 9 Material - Chrome Vanadium, QQ-W-412
Comp. I

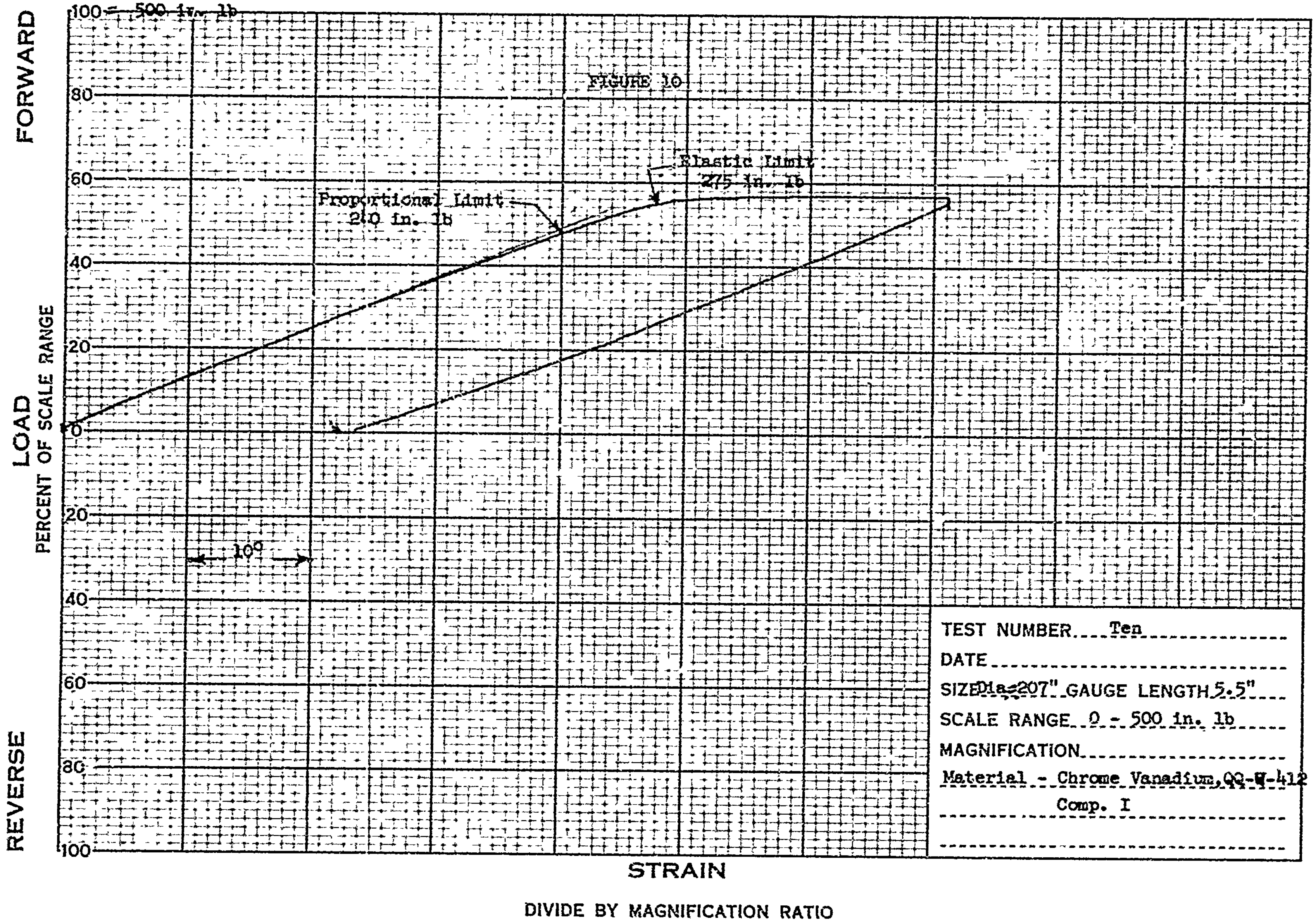

FIGURE 10

Material - Chrome Vanadium, QQ-W-412
Comp. I

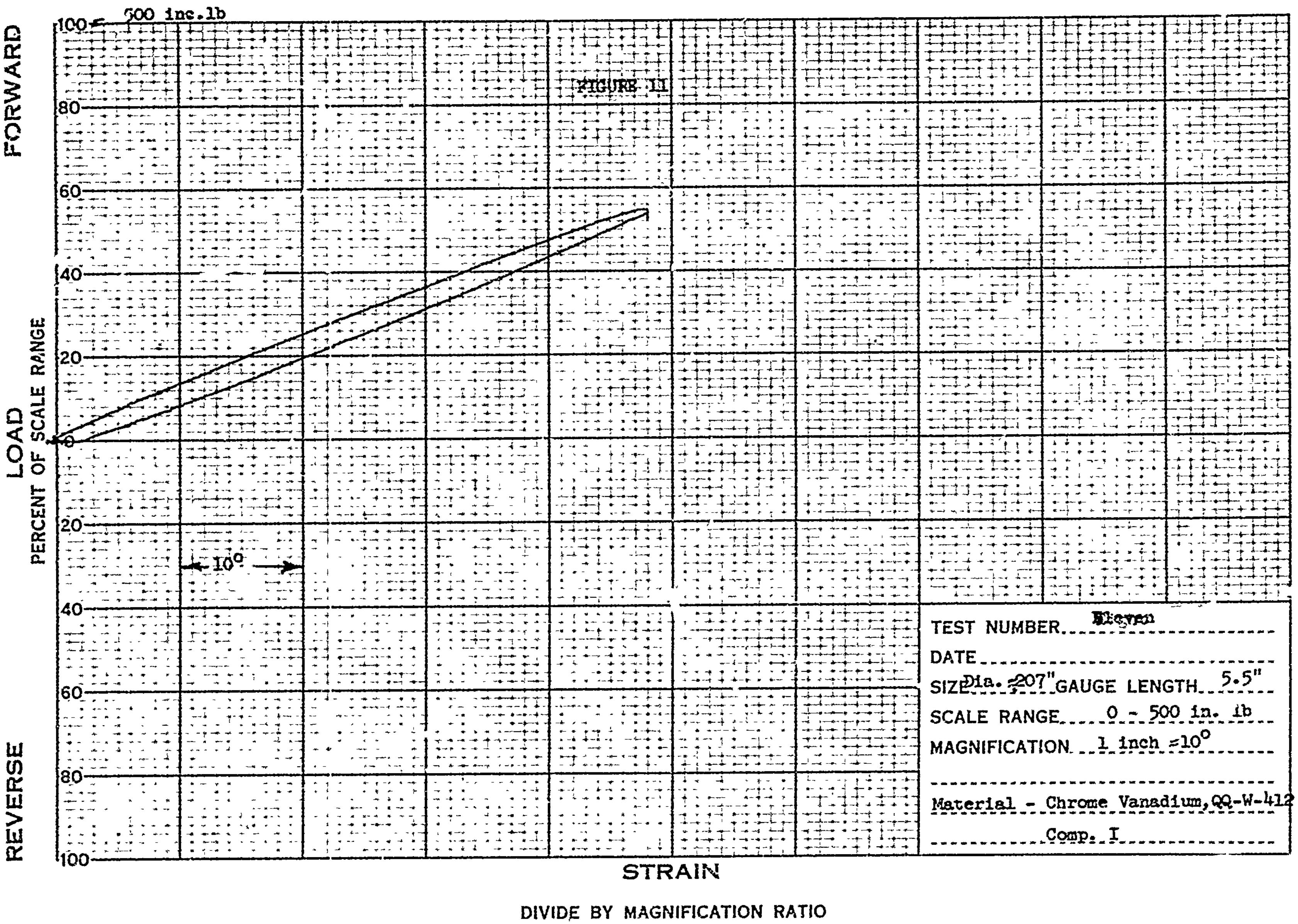

FIGURE 11 Material - Chrome Vanadium, QQ-W-412
Comp. I

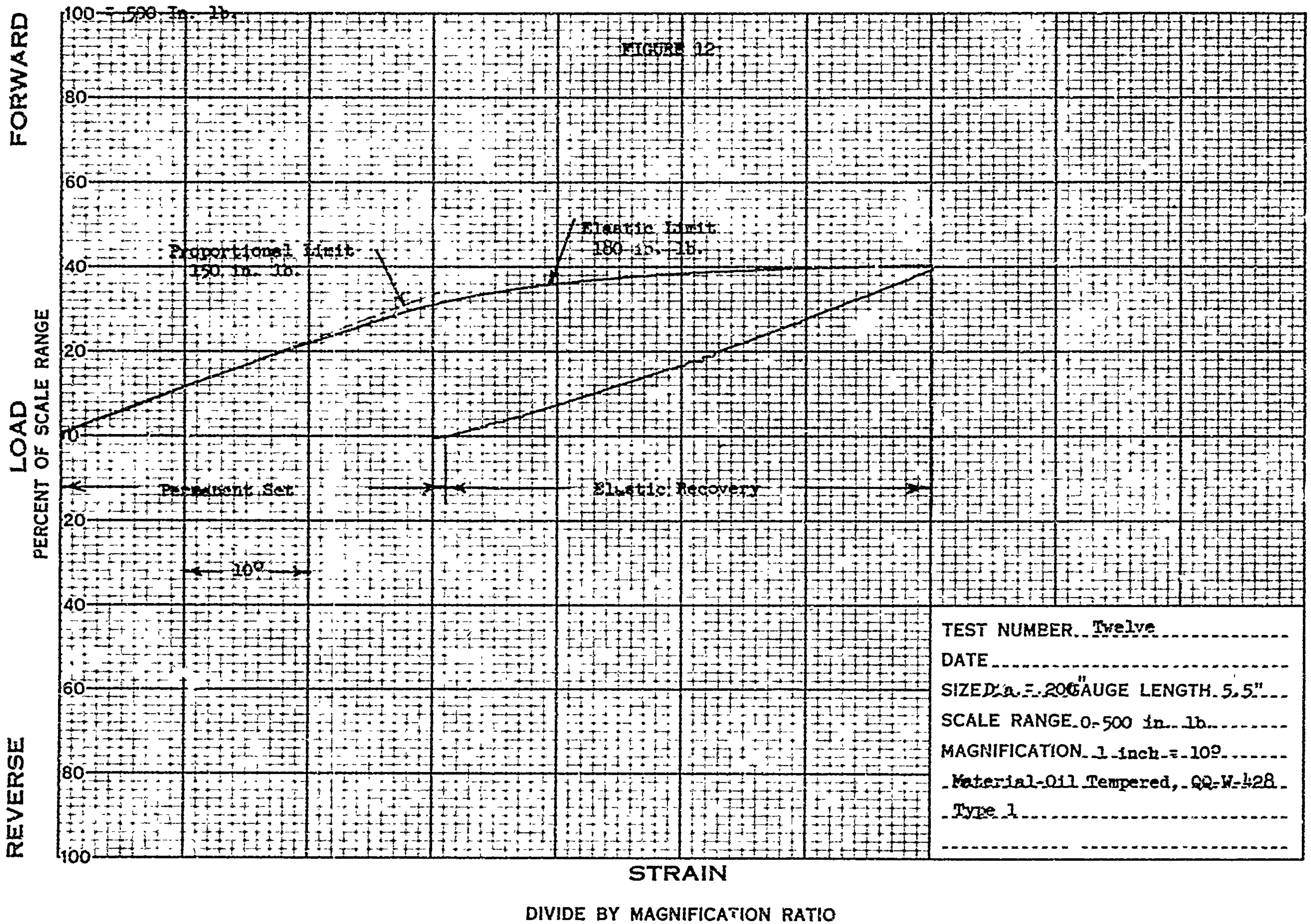

FIGURE 12 Material - Oil Tempered, QQ-W-428
Type I

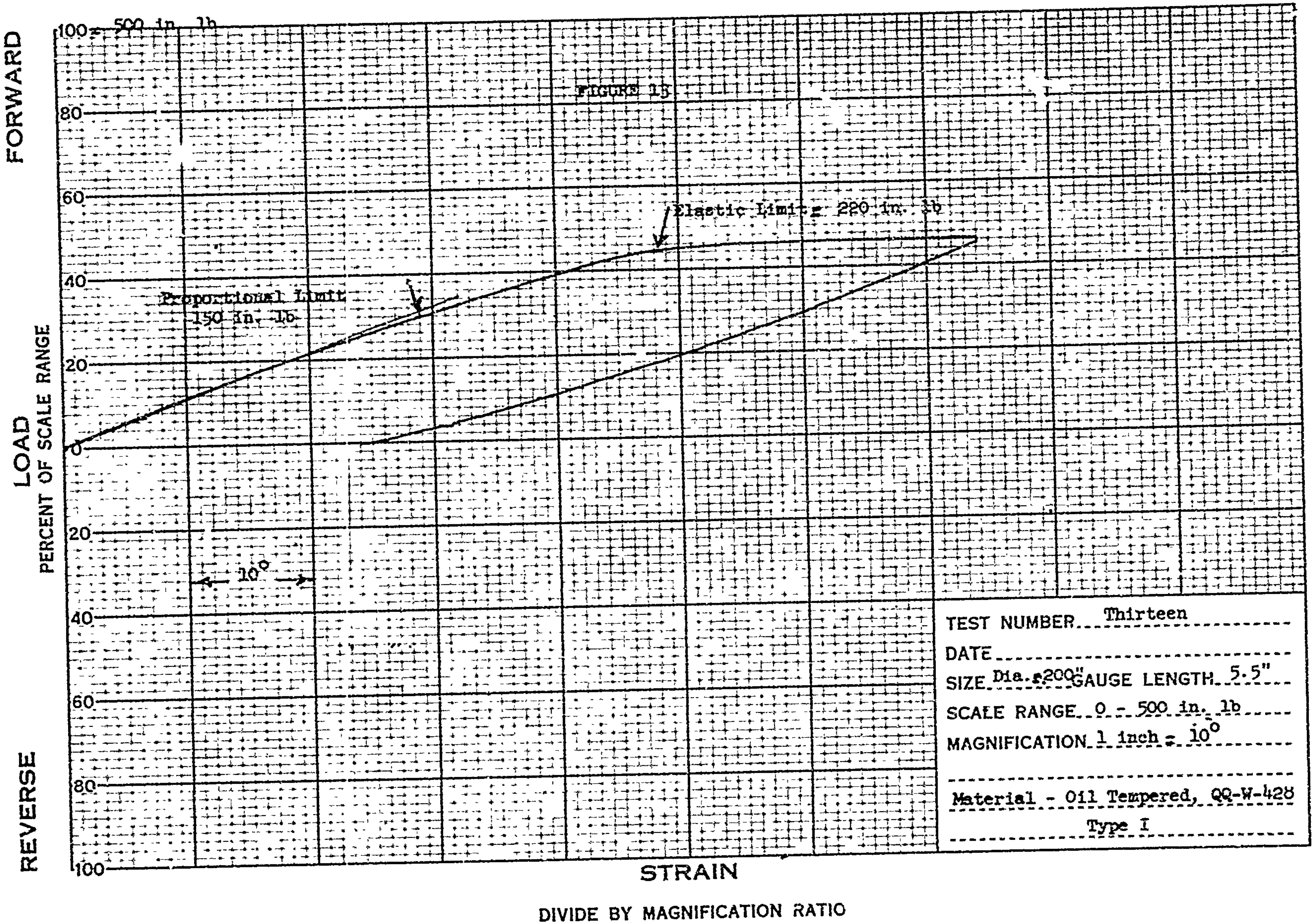

FIGURE 13

Material - Oil Tempered, QQ-W-428
Type I

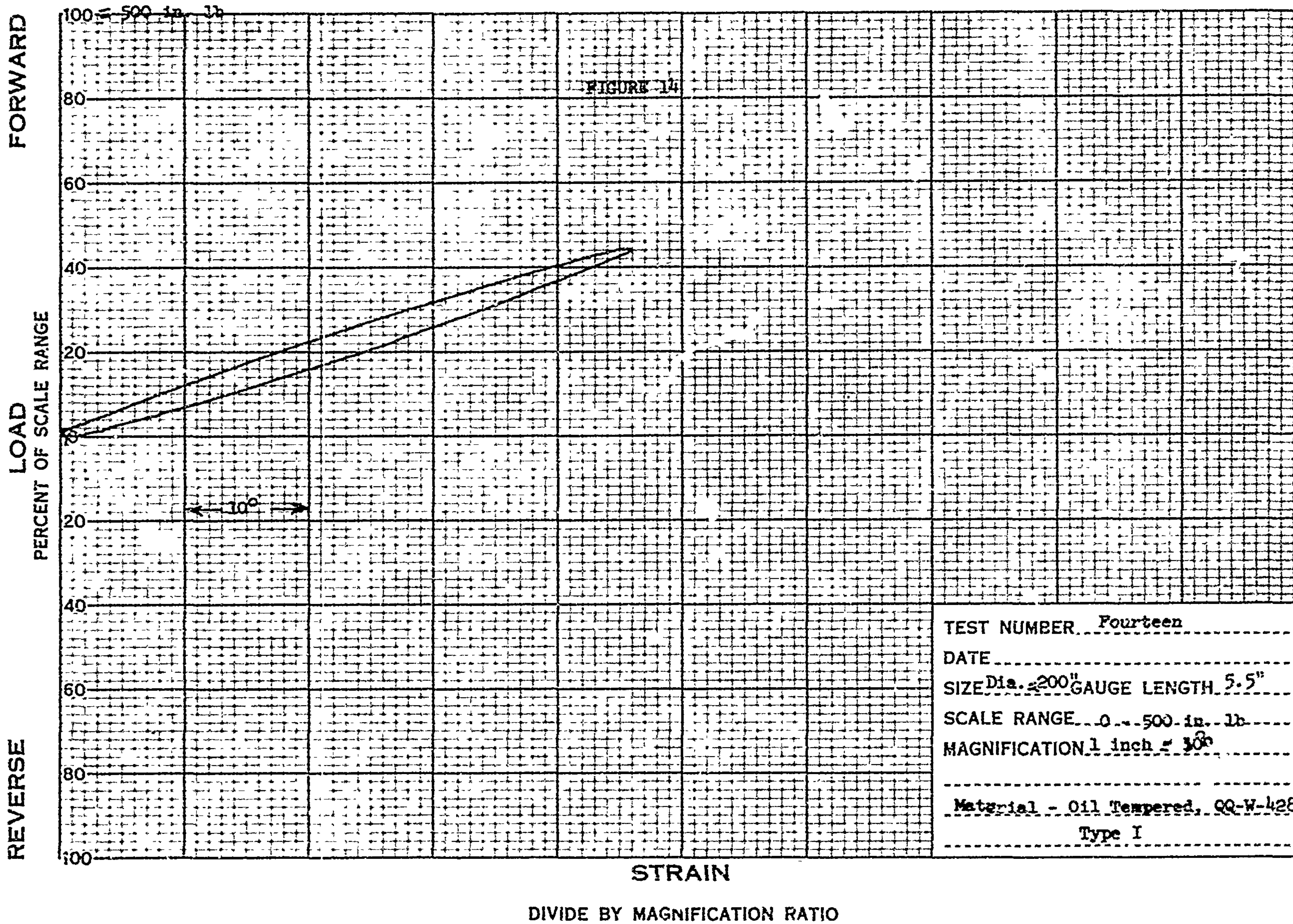

FIGURE 14 Material - Oil Tempered, QQ-W-428 Type I

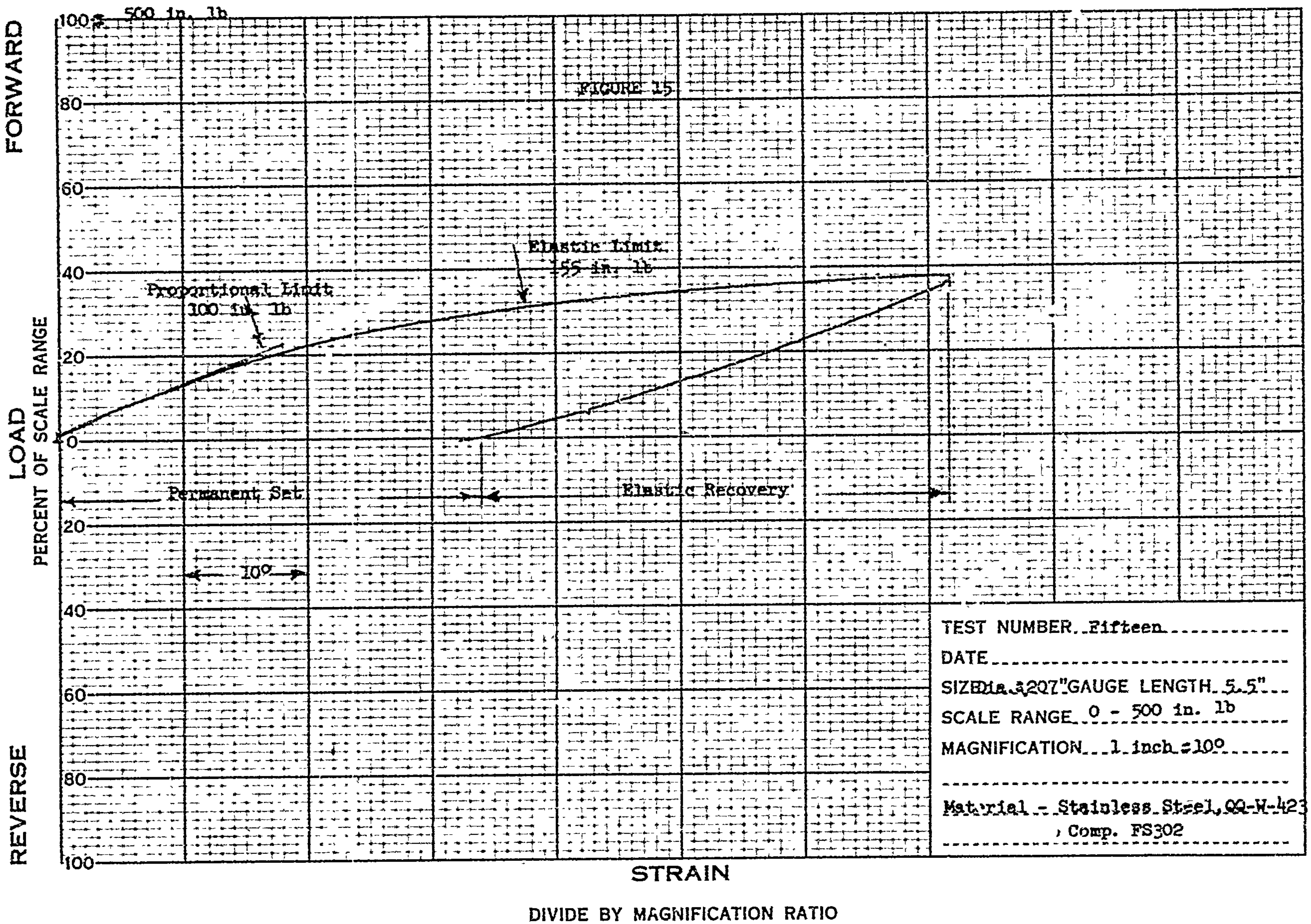

FIGURE 15 Material - Stainless Steel QQ-W-423
Comp. FS302

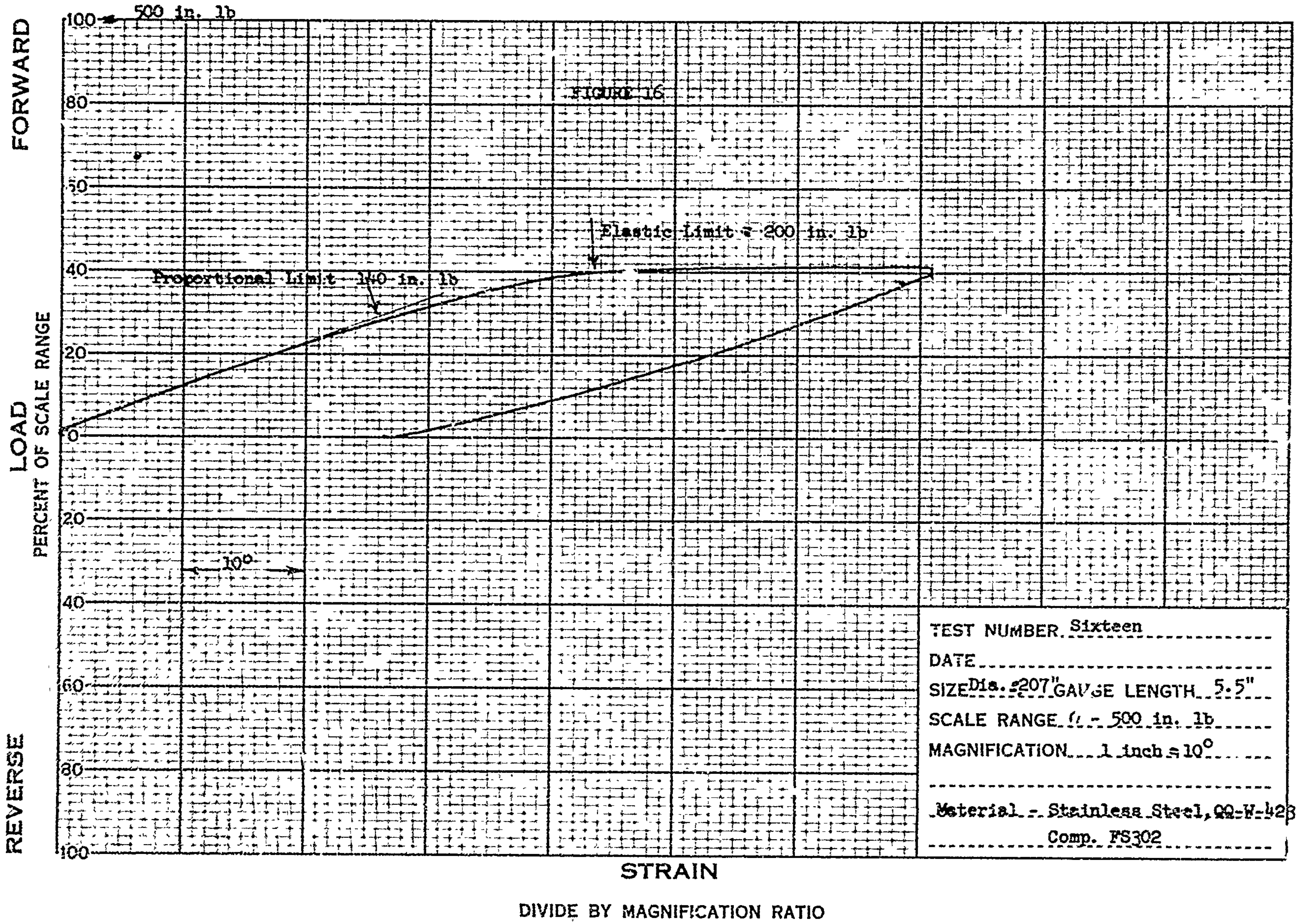

FIGURE 16 Material - Stainless Steel, QQ-W-423
Comp. FS302

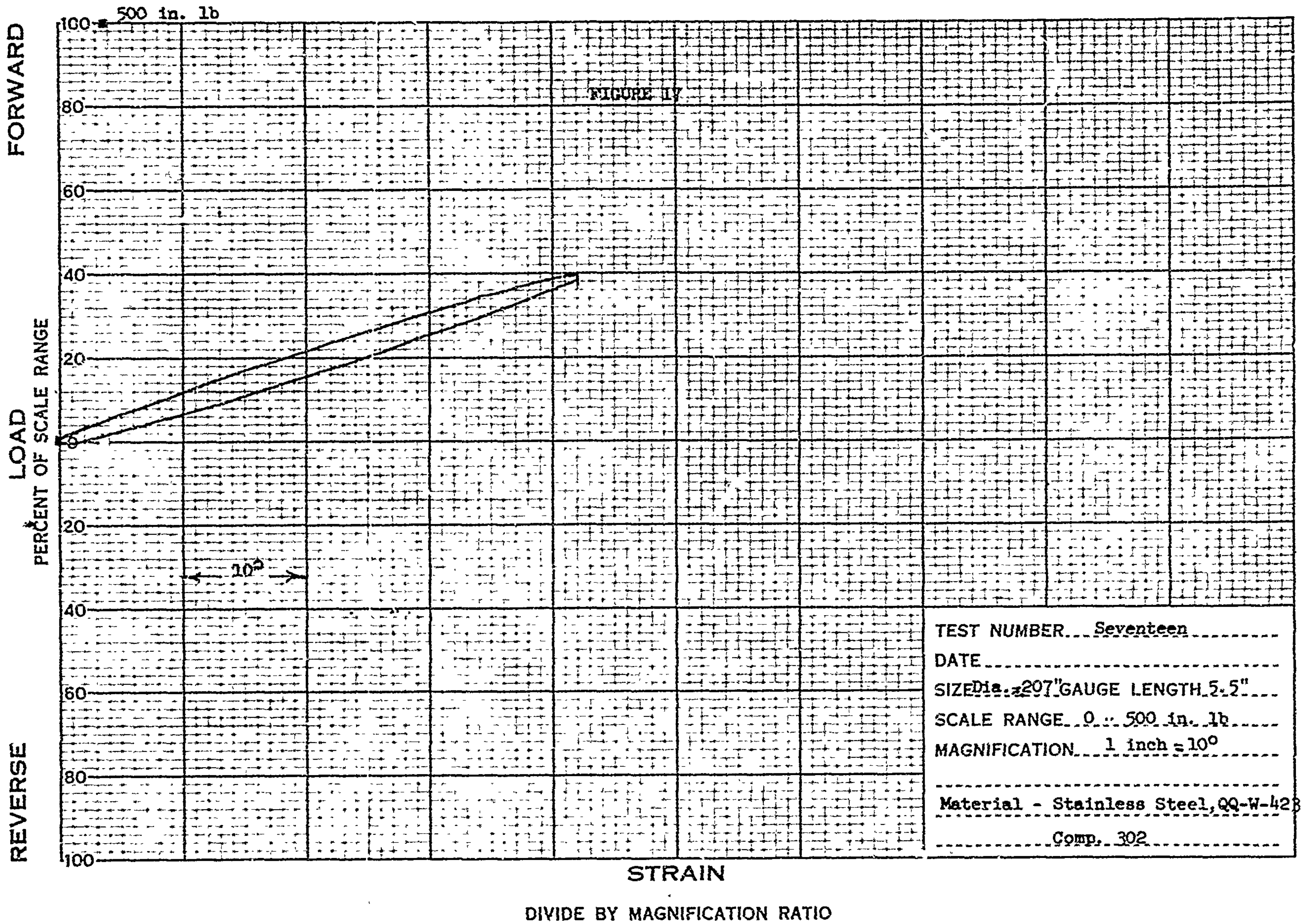

FIGURE 17 Material - Stainless Steel, QQ-W-423
Comp. 302

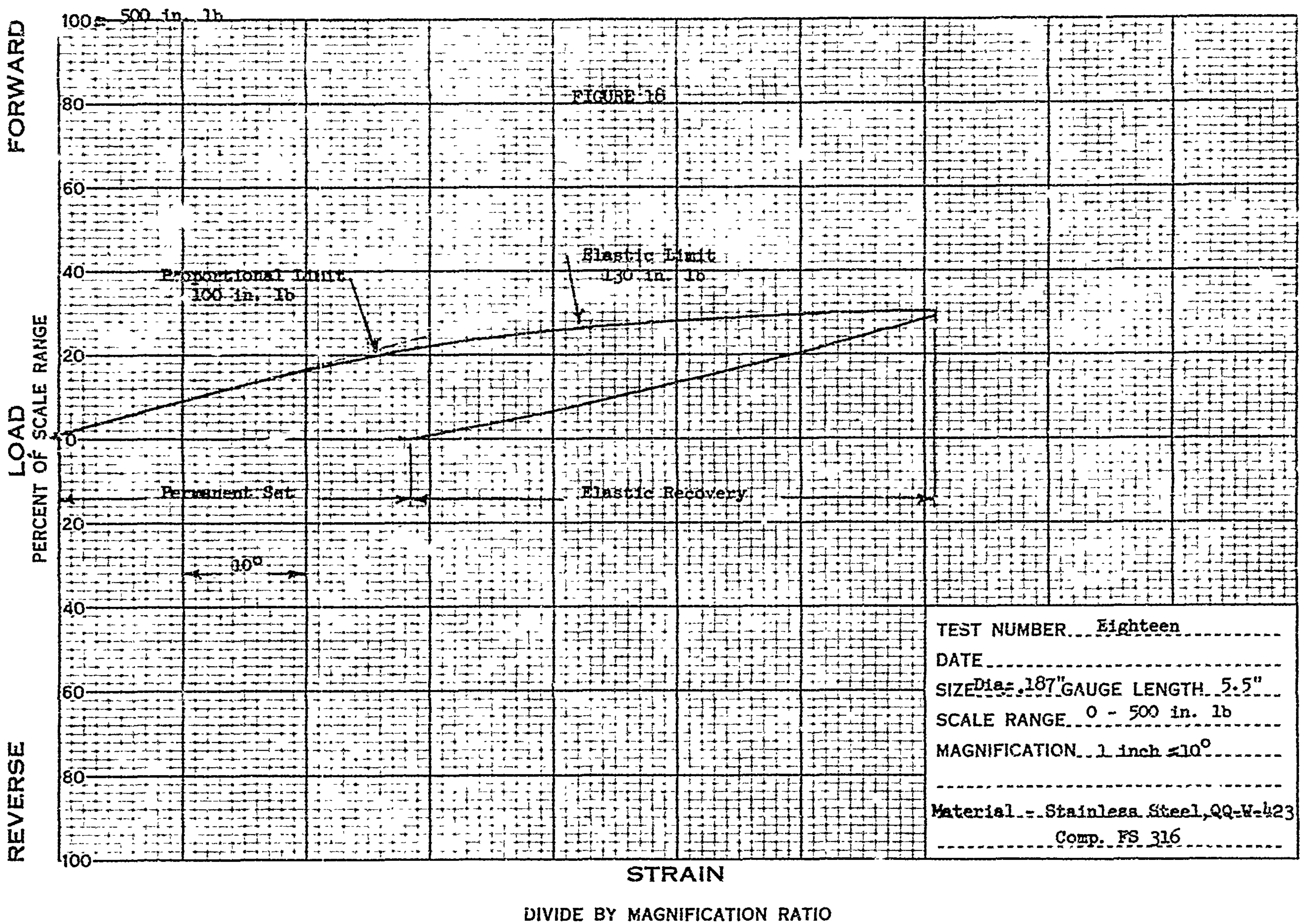

FIGURE 18 Material - Stainless Steel, QQ-W-423
Comp. FS316

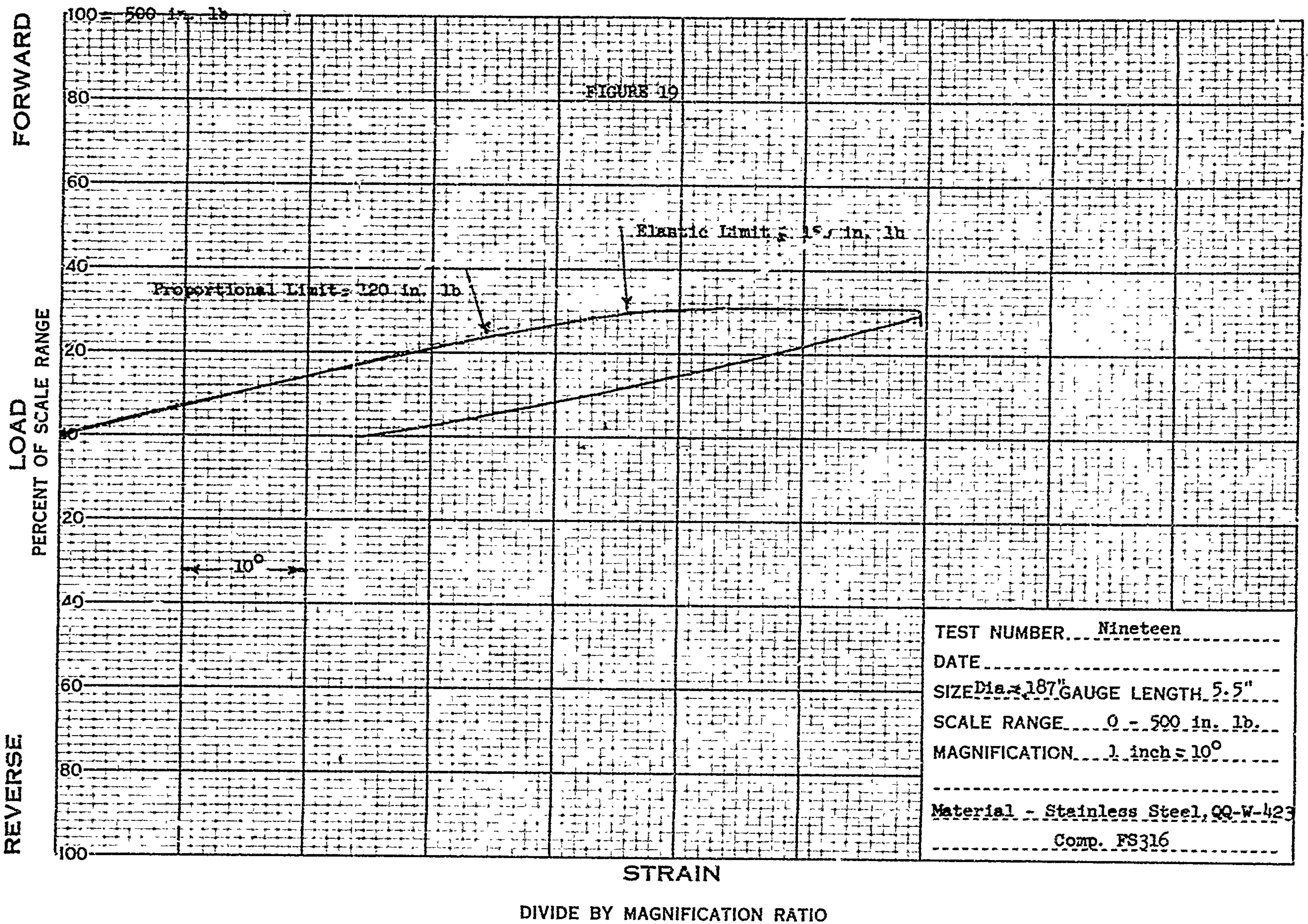

FIGURE 19   Material - Stainless Steel, QQ-W-423
Comp. FS316

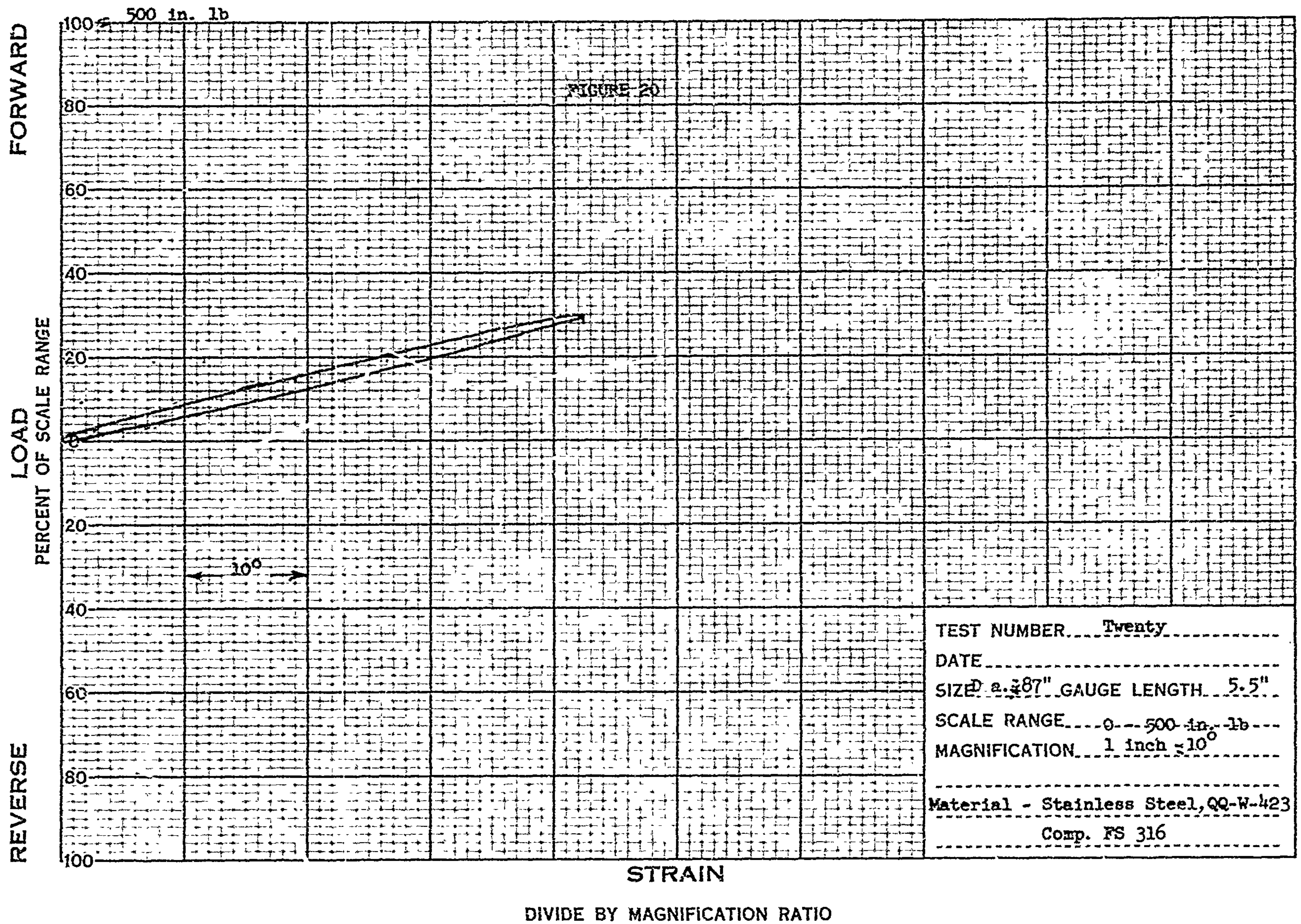

FIGURE 20 Material - Stainless Steel, QQ-W-423
Comp. FS316

TABLE 1

Material	Music Wire	Hard Drawn	Chrome Vanadium	Oil Tempered	Stainless Steel	Stainless Steel
	QQ-W-470	QQ-W-428	QQ-W-412	QQ-W-428	FS 302	FS 316
Wire Size, in.	.200	.207	.207	.200	.207	.187
Initial Proportional Limit, in. lb	150	150	190	150	100	100
Final Proportional Limit, in. lb	160	160	240	150	140	120
Initial Elastic Limit, in. lb	205	200	225	180	155	130
Final Elastic Limit, in. lb	250	250	275	220	200	150
Stress at Initial Elastic Limit, psi	131,000	115,000	129,000	115,000	89,000	101,000
Stress at Final Elastic Limit, psi	159,000	144,000	158,000	140,000	115,000	117,000
Stress Increase at Elastic Limit Due to Strain Hardening, psi	28,000	29,000	29,000	25,000	26,000	16,000

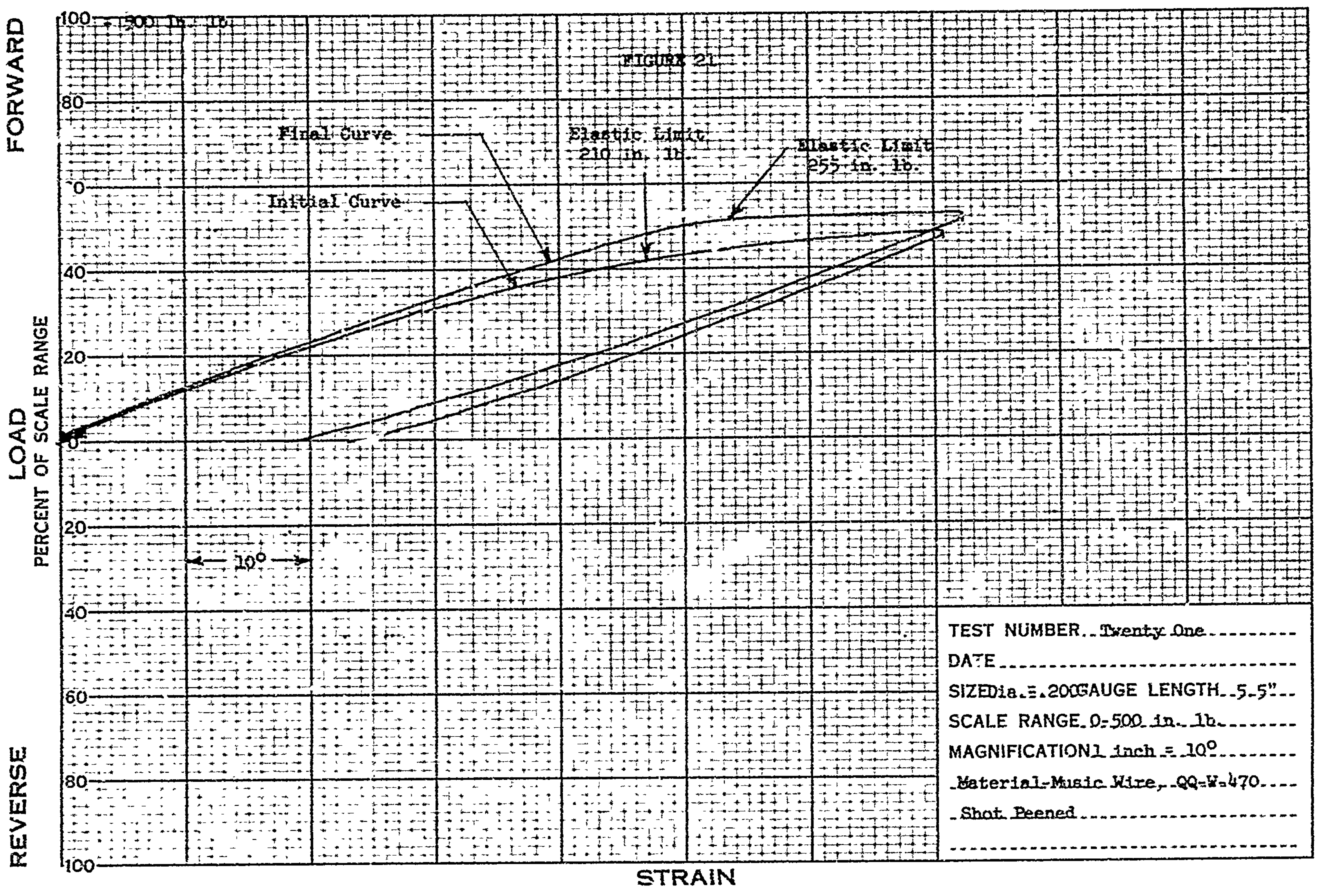

FIGURE 21 Material - Music Wire, QQ-W-470
Shot Peened

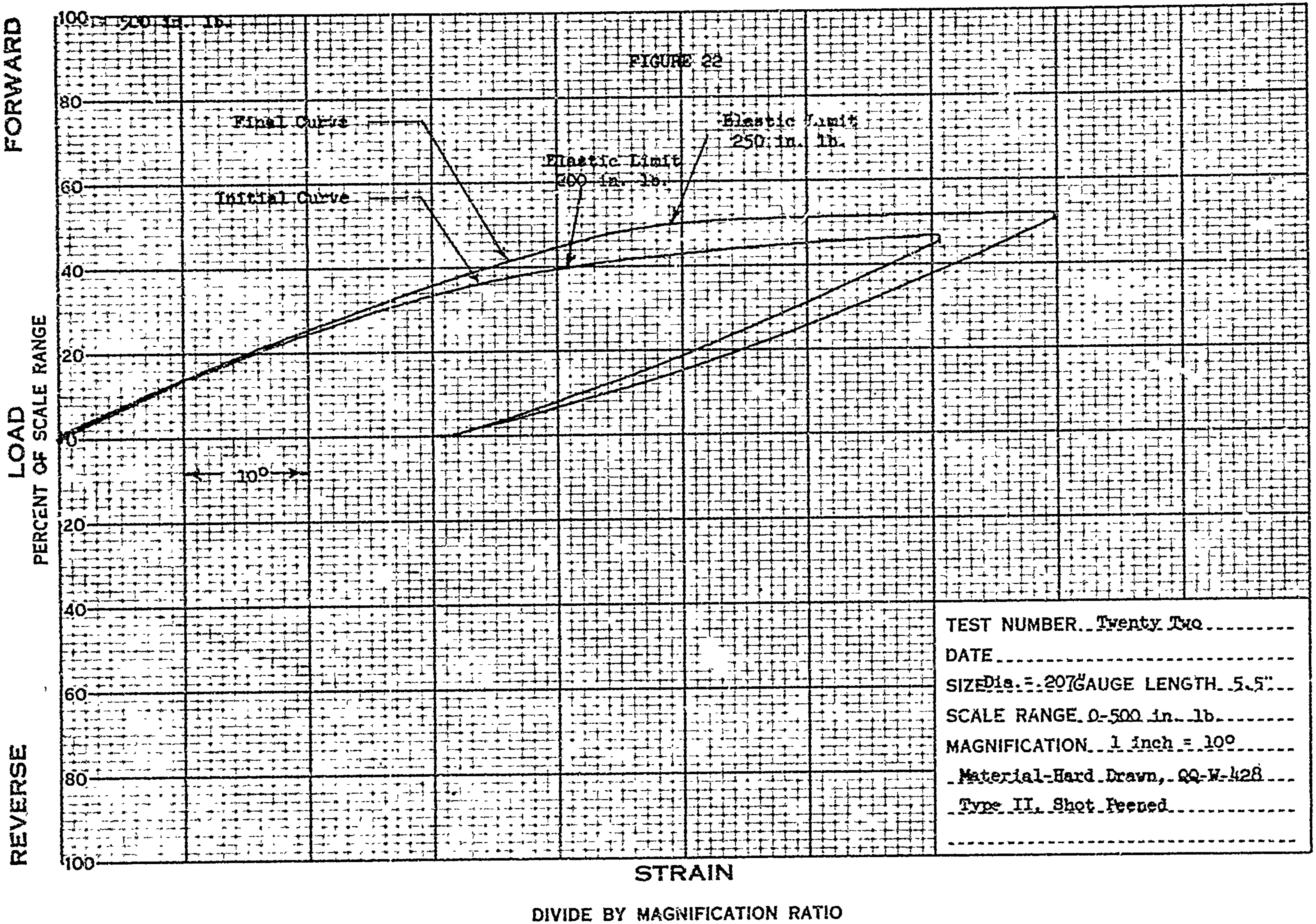

FIGURE 22

Material - Hard Drawn, QQ-W-428
Type II, Shot Peened

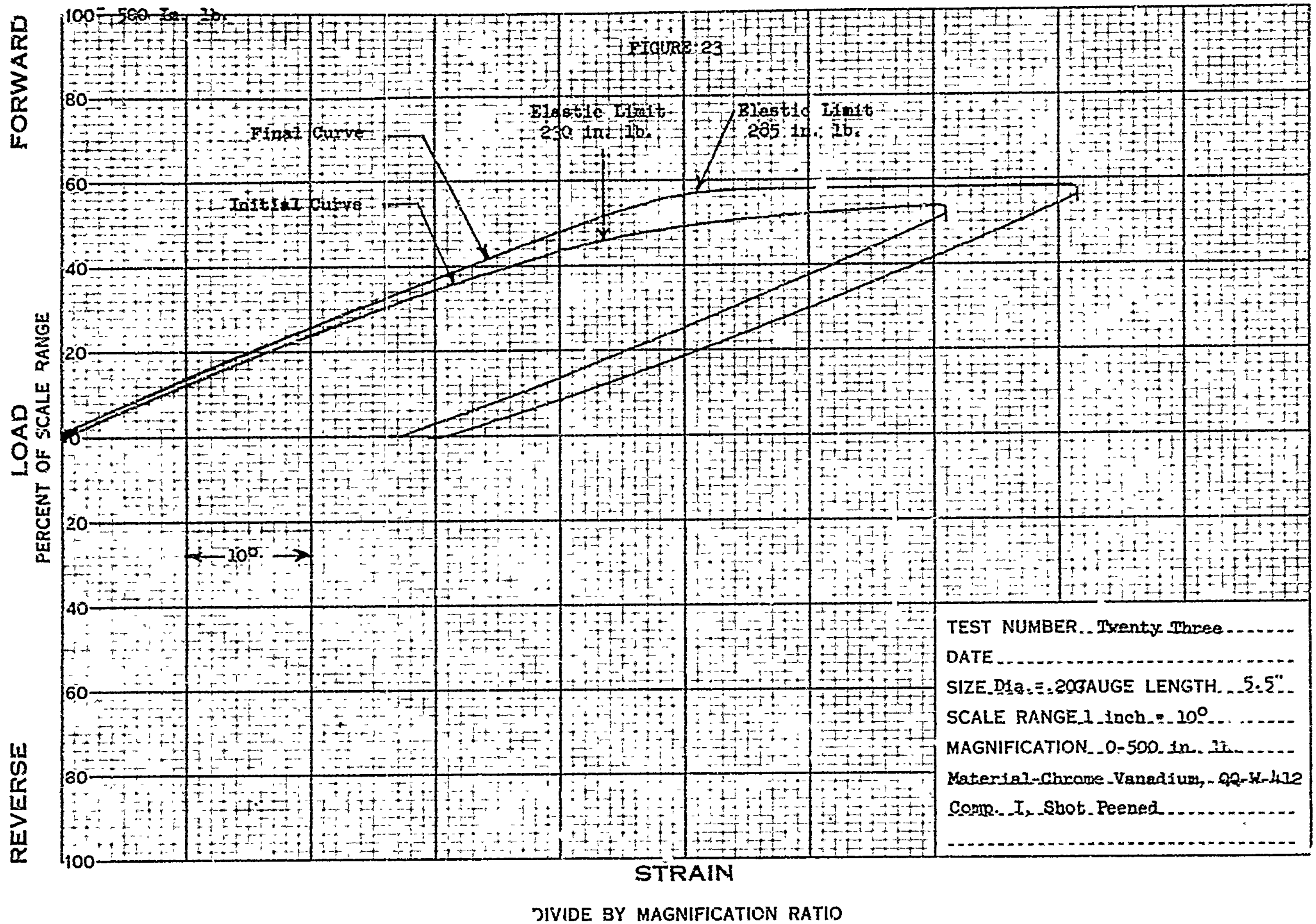

FIGURE 23

Material - Chrome Vanadium, QQ-W-412
Comp. I, Shot Peened

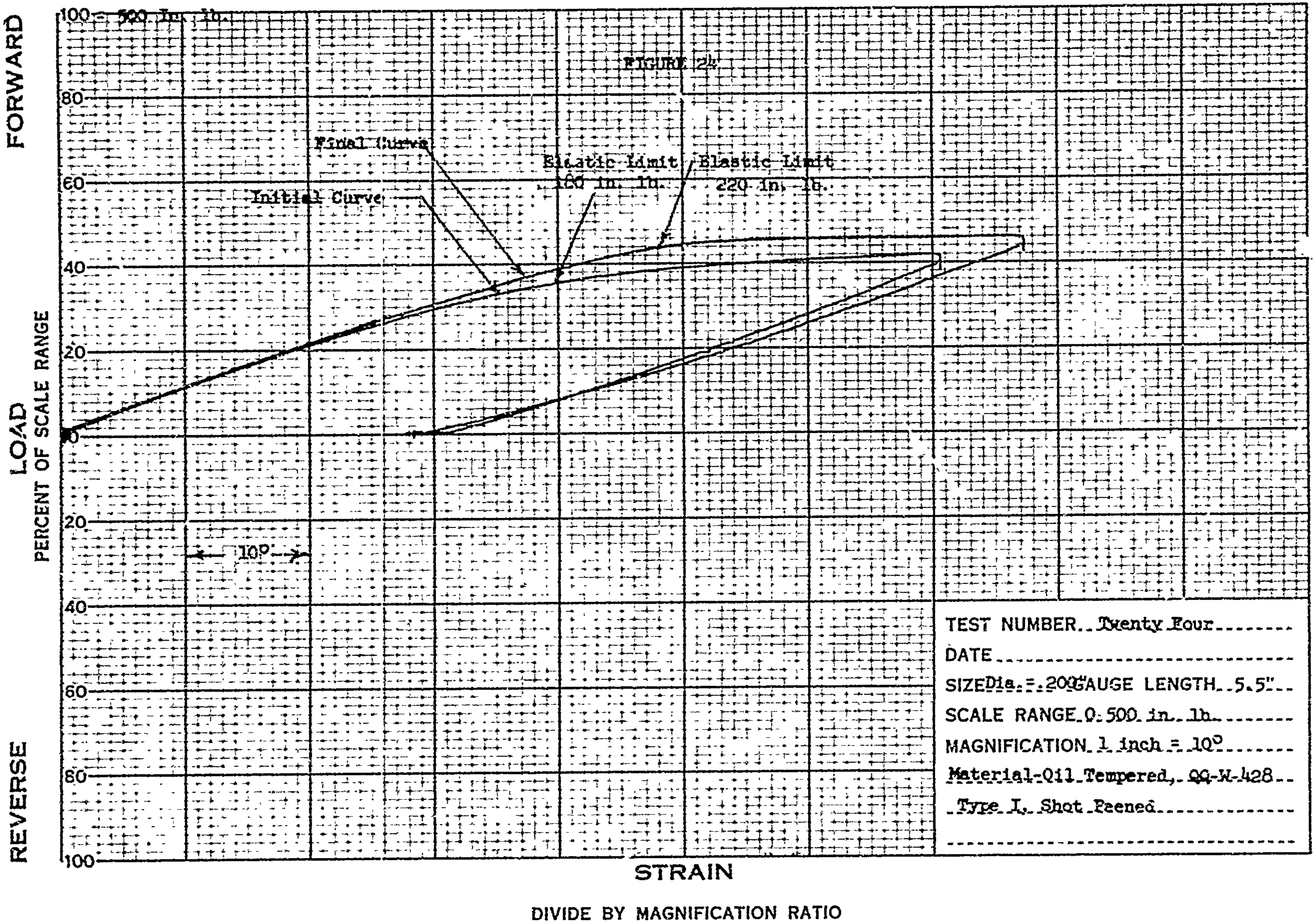

FIGURE 24

Material - Oil Tempered, QQ-W-428
Type I, Shot Peened

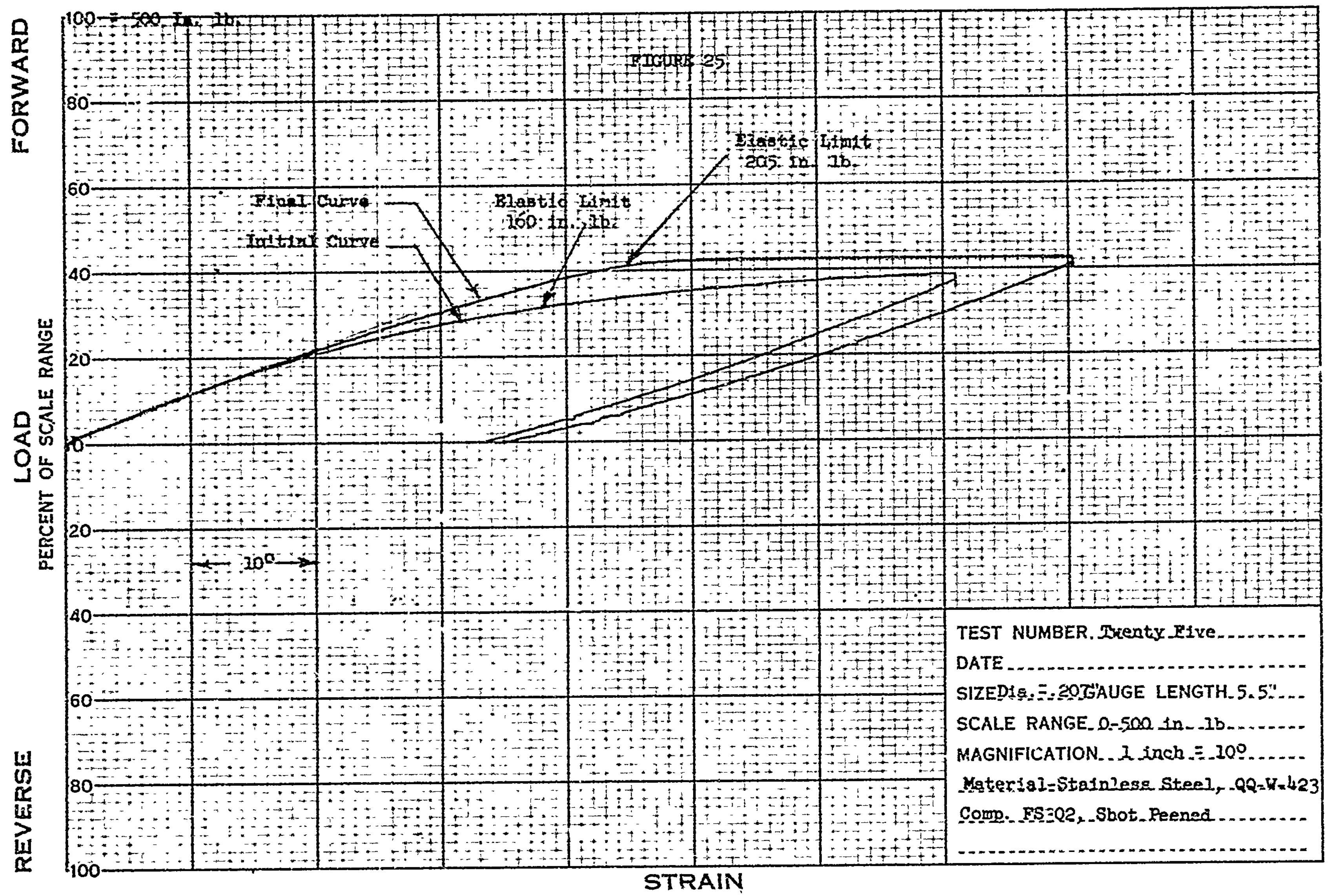

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FIGURE 25 Material - Stainless Steel, QQ-W-423
Comp. FS302, Shot Peened

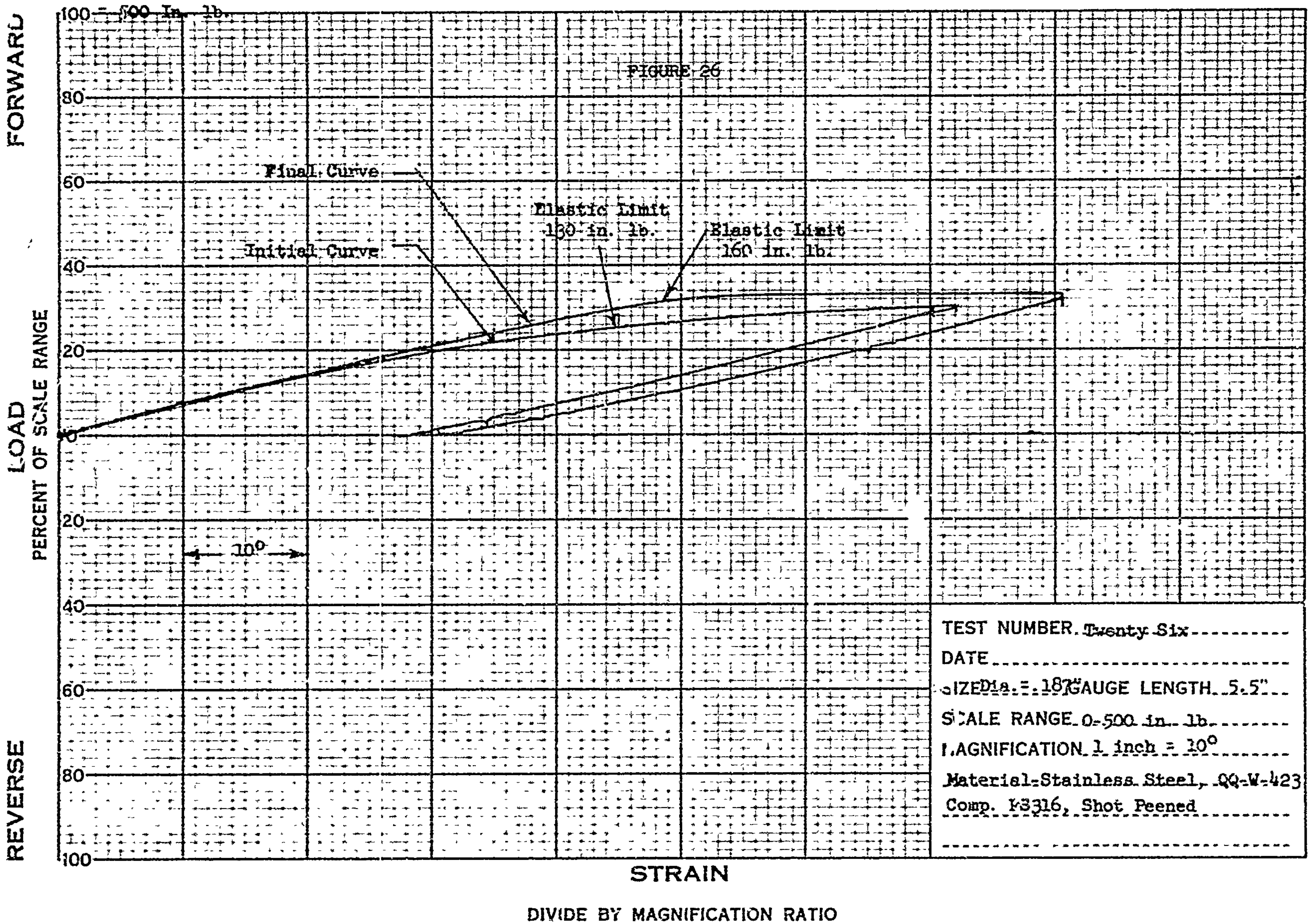

FIGURE 26 Material - Stainless Steel, QQ-W-423
Comp. FS316, Shot Peened

TABLE 2

Material	Music Wire		Hard Drawn		Chrome Vanadium		Oil Tempered		Stainless Steel		Stainless Steel	
	QQ-W-470		QQ-W-428		QQ-W-412		QQ-W-428		FS 302		FS 316	
	Not Shot Peened	Shot Peened	Not Shot Peened	Shot Peened	Not Shot Peened	Shot Peened	Not Shot Peened	Shot Peened	Not Shot Peened	Shot Peened	Not Shot Peened	Shot Peened
Wire Size in.	.200	.200	.207	.207	.207	.207	.200	.200	.207	.207	.187	.187
Initial Elastic Limit, in. lb	205	210	200	200	225	230	180	180	155	160	130	130
Final Elastic Limit, in. lb	250	255	250	250	275	285	220	220	200	205	150	160
Stress at Initial Elastic Limit, psi	131,000	134,000	115,000	115,000	129,000	132,000	115,000	115,000	89,000	92,000	101,000	101,000
Stress at Final Elastic Limit, psi	159,000	163,000	144,000	144,000	158,000	164,000	140,000	140,000	115,000	118,000	117,000	125,000

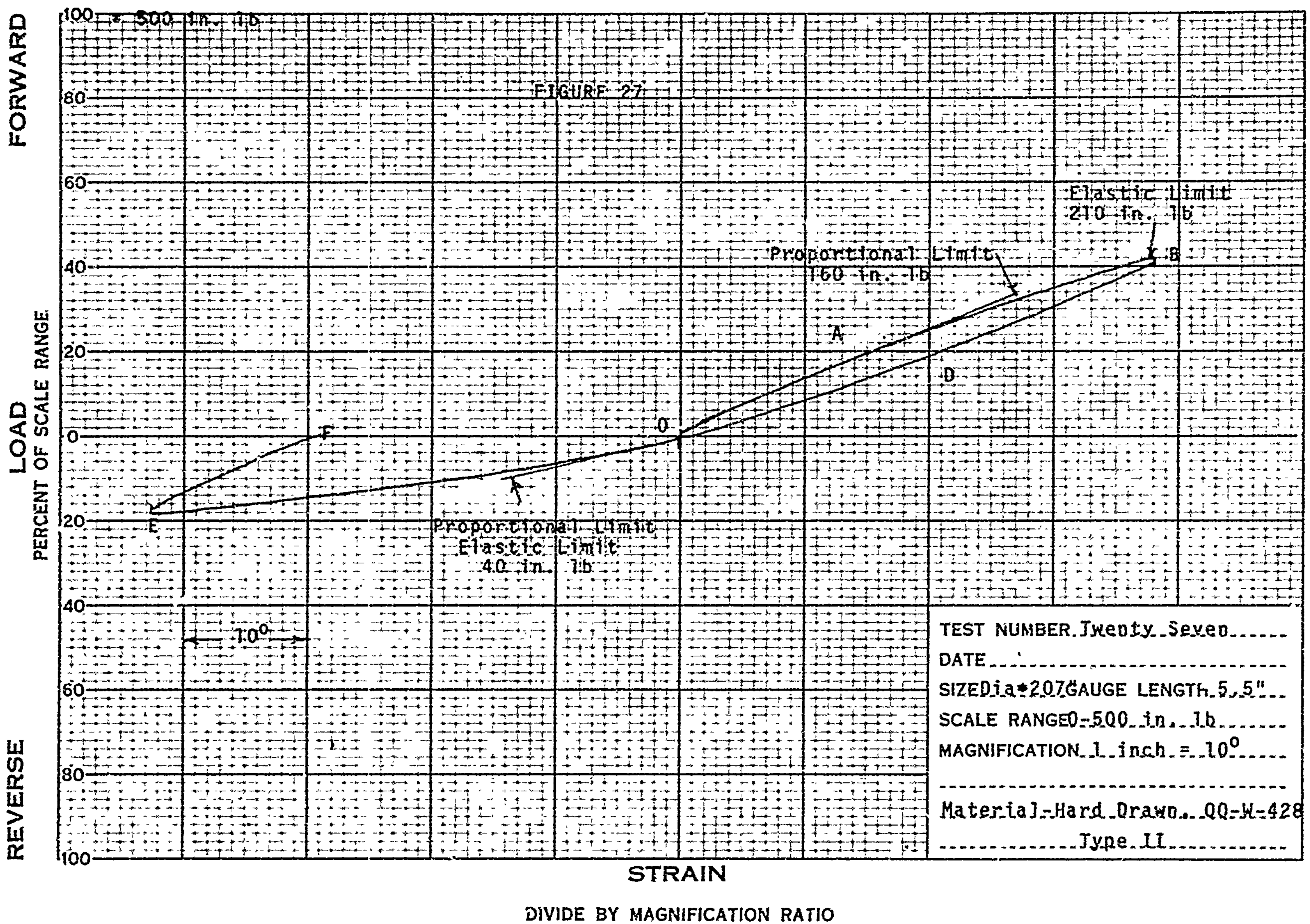

FIGURE 27 Material - Hard Drawn, QQ-W-428 Type II

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1. Eshbach, O. W., Handbook of Engineering Fundamentals, John Wiley & Sons, Inc., New York, New York, 1936.

2. Richards, C. W., Engineering Materials Science, Wadsworth Publishing Company, Inc., San Francisco, California, 1961